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Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/Thermospheric Research: Report of a Workshop

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Research conducted by the ionospheric modifications (IM) community -- a community that uses high-frequency (HF) transmitters to inject energy in the ionosphere and measure its effects using ground and space-based diagnostics -- is focused on understanding the interaction of radio waves with the ionospheric plasma, the local consequences of heating in the ionosphere, and studies of nonlinear plasma physics processes. At the request of the Department of Defense (DOD) Air Force Research Laboratory (AFRL) and the National Science Foundation (NSF) Directorate for Geosciences/Division of Atmospheric and Geospace Sciences, the Space Studies Board of the National Research Council held a workshop on May 20-21, 2013, in Washington, D.C., entitled “The Role of High-Power, High Frequency-Band Transmitters in Advancing Ionospheric/Thermospheric Research.” The request for this workshop was informed by the sponsors’ awareness of the possibility that tight budgets would result in DOD’s curtailment, or even termination, of support for the High Frequency Active Auroral Research Program (HAARP), which includes the world’s highest-power and most capable HF transmitter -- “heater” -- for ionospheric research. Although the workshop was organized to consider the utility of heaters in upper atmospheric research in general, it had a specific focus on the HAARP transmitter facility, which is located in a remote part of southeastern Alaska.

Conference Name: Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/Thermospheric Res

Conference Date: May 20, 2013

Opportunities for
High-Power, High-Frequency Transmitters to Advance Ionospheric/ Thermospheric Research

Report of a Workshop

Committee on the Role of High-Power, High-Frequency-Band Transmitters in Advancing Ionospheric/Thermospheric Research: A Workshop

Space Studies Board

Division on Engineering and Physical Sciences

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COMMITTEE ON THE ROLE OF HIGH-POWER, HIGH-FREQUENCY-BAND TRANSMITTERS IN ADVANCING IONOSPHERIC/THERMOSPHERIC RESEARCH: A WORKSHOP

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Preface

At the request of the Department of Defense (Air Force Research Laboratory) and the National Science Foundation (NSF; Directorate for Geosciences/Division of Atmospheric and Geospace Sciences), the Space Studies Board of the National Research Council (NRC) held a workshop on May 20-21, 2013, in Washington, D.C., entitled “The Role of High-Power, High Frequency-Band Transmitters in Advancing Ionospheric/Thermospheric Research.” The workshop provided a forum for information exchange between the comparatively small group of scientists engaged in programs of upper atmospheric research using high-power, high-frequency (HF) radar transmitters (“heaters”) and the larger ITM (ionosphere-thermosphere-magnetosphere) research community. For a variety of reasons—including the different orientations of the Department of Defense, which is primarily interested in applied research related to active ionospheric modification,[1] and the civil agencies, principally NSF, which have broader mandates for basic research—these communities have historically viewed themselves as being distinct with limited overlapping interests.

As indicated in the terms of reference (“statement of task”) developed by the sponsors (see Appendix A), the workshop was organized to consider the utility of heaters in upper atmospheric research in general, with a specific focus on the High Frequency Active Auroral Research Program (HAARP) transmitter facility, which is located in Gakona, Alaska. The motivations for the workshop were twofold. First, the sponsors of the workshop were aware of the potential—one that became increasingly apparent during the period between project approval by the NRC in late Spring 2012 and the actual workshop in late Spring 2013—for substantial cutbacks in support by the Air Force for the continuing operation of HAARP.[2] Second, NSF’s upper atmosphere research section is considering transfer to Gakona, Alaska, of the AMISR (Advanced Modular Incoherent Scatter Radar) re-locatable modular phased-array radar, located at Poker Flat, Alaska (thus, known as PFISR), for joint research campaigns with the HAARP transmitter and ancillary instruments. Although the original statement of task was never revised, the organizers were keenly aware of the increasing interest among the sponsors for focused discussions on the HAARP facility. The workshop agenda and the preponderance of discussions at the workshop reflect these interests.

The workshop agenda and a list of participants are shown in Appendixes B and C, respectively, and biographical information about the workshop organizing committee is shown in Appendix D. *While the committee is responsible for the overall quality and accuracy of the report as a record of what transpired at the workshop, the views contained in the report are not necessarily those of all workshop participants, the committee, or the NRC. It should also be recognized that the report summarizes, but does not evaluate critically, the assertions made by participants of the potential utility for high-power, high-frequency transmitters or the HAARP facility.* Finally, although the authors of this summary have attempted to provide context for the often highly technical discussions that took place, the summary is not intended to be a primer on heaters in general, HAARP in particular, or current issues in upper atmosphere research.

[1] The use of high-power transmitters, such as the one located at the HAARP facility, to study the upper atmosphere is called “active ionospheric research.”

[2] In fact, the HAARP facility ceased operations shortly after the workshop—due to pending contractor changes and an as yet unfunded need to upgrade the diesel power generators per Environmental Protection Agency regulations—and remains closed at the time of this printing.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Umran S. Inan, Koç University, Turkey,
Larry J. Paxton, Johns Hopkins University Applied Physics Laboratory,
Joshua Semeter, Boston University, and
Jeffrey P. Thayer, University of Colorado, Boulder.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse any of the viewpoints or observations detailed in this report, nor did they see the final draft of the report before its release. The review of this report was overseen by Robert J. Serafin, National Center for Atmospheric Research. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Overview

Research conducted by the ionospheric modifications (IM) community—a community that uses high-frequency (HF) transmitters to inject energy in the ionosphere and measure its effects using ground- and space-based diagnostics—is focused on understanding the interaction of radio waves with the ionospheric plasma, the local consequences of heating in the ionosphere, and studies of nonlinear plasma physics processes. At the request of the Department of Defense (DOD) Air Force Research Laboratory (AFRL) and the National Science Foundation (NSF) Directorate for Geosciences/Division of Atmospheric and Geospace Sciences, the Space Studies Board of the National Research Council held a workshop on May 20-21, 2013, in Washington, D.C., entitled "The Role of High-Power, High Frequency-Band Transmitters in Advancing Ionospheric/Thermospheric Research." The request for this workshop was informed by the sponsors' awareness of the possibility that tight budgets would result in DOD's curtailment, or even termination,[1] of support for the High Frequency Active Auroral Research Program (HAARP), which includes the world's highest-power and most capable HF transmitter—"heater"—for ionospheric research. Although the workshop was organized to consider the utility of heaters in upper atmospheric research in general (see Appendix A), it had a specific focus on the HAARP transmitter facility, which is located in a remote part of southeastern Alaska (Figure S.1).[2]

The HAARP facility began construction in 1993; it was completed in 2007 at an estimated total cost of $290 million.[3] The facility's principal instrument for study of the ionosphere is a transmitter array of 180 crossed dipoles that are spaced over an area of about 30 acres. The dipoles are arranged in a 12 by 15 rectangular grid and are phased to provide steering; together, they can produce up to 3,600 kW of radiated power in a band from 2.8 to 10 MHz, which falls within what is commonly referred to as the HF band (3-30 MHz) of the electromagnetic spectrum.

The HAARP program is sponsored by DOD, receiving support from the Navy, the Air Force, and the Defense Advanced Research Projects Agency (DARPA). Its objectives are to "identify, investigate, and, if feasible, control ionospheric processes and phenomena that might serve to enhance future DOD Command, Control and Communications capabilities . . . research areas that will be explored include generation of very low and extremely low frequency waves, generation of geomagnetic field-aligned irregularities, electron acceleration, and investigation of upper atmospheric processes."[4] Figure S.2 illustrates operation of the HAARP transmitter—known as an ionospheric "heater" because most of the transmitted energy goes into heating ionospheric electrons.

[1] At the workshop, an Air Force representative stated that current plans called for the elimination of funding for the facility starting by fiscal year 2015. Not foreseen at the time the workshop was requested, the Budget Control Act of 2011 (BCA)—"the sequester"—which took effect on March 1, 2013, resulted in further substantial cuts to the DOD budget. As noted in footnote 2 of the Preface, HAARP facility ceased operations shortly after the workshop and remains closed at the time of this printing.

[2] For an overview of heaters and ionospheric modification, see Duncan and Gordon (1982). A popular article that discusses HAARP applications is Weinberger (2008).

[3] According to a number of participants who, in turn, referenced fact sheets for HAARP.

[4] Robertshaw et al. (1993), p. 1.

FIGURE S.1 Overhead photo of the High Frequency Active Auroral Research Program Gakona Facility. SOURCE: McCarrick, M., et. al., Marsh Creek LLC, “HAARP Facility Status,” presentation to the Committee on the Role of High-Power, High-Frequency-Band Transmitters in Advancing Ionospheric/Thermospheric Research: A Workshop, April 2013. Courtesy of M. McCarrick. Available at http://www.haarp.alaska.edu/haarp/photos.html.

According to experts at the workshop, the combination of extremely high power and the capability to be rapidly reconfigured to create a variety of spatial and temporal antenna patterns is unique in the world to “HAARP,” or more properly its ionospheric research instrument (IRI).[5] Further, in presentations at the workshop, participants learned how the ability to produce such large and patterned energy into the ionosphere is being used for exploring many aspects of the upper atmosphere, including the mesosphere and lower thermosphere (MLT) region, the ionosphere, and the magnetosphere. These regions form a coupled system whose nonlinear response to variable and wide-ranging energy and momentum sources have important influences on those of us living on the surface of Earth; for example, radio and satellite communications, global navigation, and the lifetime of space assets limited by atmospheric drag. Many participants in the workshop, even some who were familiar with experiments at heater facilities, said they came away with an increased appreciation for the breadth of phenomena that are addressed by the HAARP facility.

[5] Throughout this report “HAARP” is used interchangeably with IRI except in those instances when reference is made to the HAARP facility, which includes the IRI, various diagnostic instrumentation, and other associated operational elements, or the “HAARP program,” which strictly speaking is not correct, because the “P” in HAARP refers to “Program,” but is common usage.

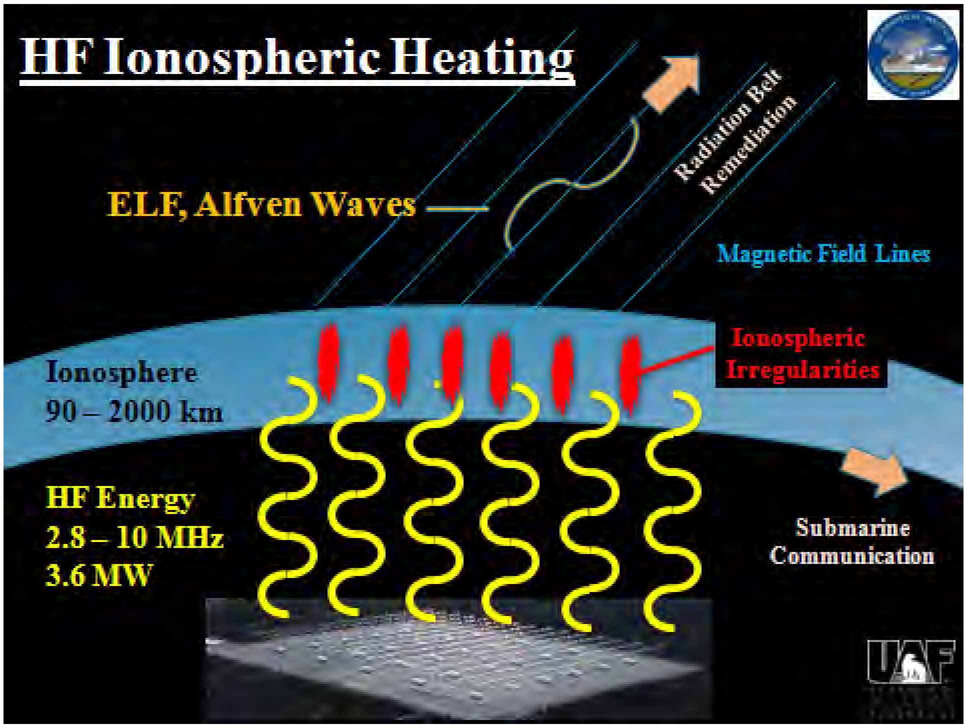

FIGURE S.2 Depiction of high-frequency ionospheric heating by the High Frequency Active Auroral Research Program transmitter. SOURCE: Courtesy of Robert McCoy, Geophysical Institute, University of Alaska, Fairbanks.

Historically, military applications have been a major motivation for studies at HAARP. At the workshop, the Navy's interest in HAARP was attributed to the prospects to use the ionosphere as an antenna to generate extremely low-frequency (ELF) waves for global submarine communication, while the Air Force interest included applications such as over-the-horizon radar and attempts to study the effects of injecting ULF, ELF, and VLF waves into the radiation belts in order to affect the lifetimes of "killer" million-electron-volt electrons that would otherwise disable low Earth orbit satellites.[6] Those applications were not widely discussed in this unclassified workshop, although some of them are mentioned in Chapter 4.

Some participants at the workshop cited the unusual history of the HAARP facility as a contributor to its underutilization by a broader community of researchers. In particular, they noted that initial funding for HAARP came from congressional earmarks that went directly to the Air Force without the same level of documentation and justification as a peer-reviewed facility. This funding history and the facilities' origins in the defense community may have contributed to the perception, as described by some participants, that performing experiments at HAARP was unduly difficult; these participants also stated that it may have contributed to HAARP's capabilities, as described above, not being widely appreciated.

For example, CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions) is an NSF-sponsored upper atmospheric research program whose goal is "to understand the behavior of atmospheric regions from the middle atmosphere upward through the thermosphere and ionosphere into the exosphere in terms of coupling, energetics, chemistry, and dynamics on regional and global scales."[7] Yet some participants noted that at summer CEDAR workshops there was little mention of research using the

[6] ELF and VLF refer to extremely low frequency and very low frequency, respectively. This part of the electromagnetic spectrum is commonly said to range from 300 Hz to 30 kHz.

[7] National Science Foundation, Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR), available at http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5503.

HAARP facility. At various points in this workshop, participants proposed ways to make the facility more welcoming and user-friendly in the future and better coordinated with the CEDAR community. Chapter 6 describes some of these proposals; in particular, NSF representatives at the workshop discussed their desire to move the Poker Flat, Alaska, advanced modular incoherent scatter radar (PFISR) to the HAARP site in Gakona, Alaska. Experiments with the combined facility could then come under the usual NSF procedures for user facilities, which are more open and familiar to many scientists.

The sponsors of the workshop posed seven questions for consideration by participants. These questions were examined in presentations and discussions that occurred in multiple sessions of the workshop; a compilation of individual participant responses follows.

1. What is the state of the art in active ionospheric and thermospheric research?

Active ionospheric research is founded in controlling the extent and altitude of absorption of power delivered by ground-based heaters into the lower ionosphere, a highly nonlinear physical phenomenon. It has been found that the response of the geophysical environment changes discontinuously as the HF power delivered to the ionosphere increases, thus indicating the presence of thresholds (Figure S.3).

As illustrated in Figure S.3, at modest powers one can achieve measurable electron and ion heating, create field-aligned striations, modulate the D/E region conductivity, and drive parametric instabilities accompanied by stimulated electromagnetic emissions and enhanced optical emissions. All of these phenomena were explored prior to the development of HAARP. In designing HAARP, there were requirements for flexible operation—a feature of phased arrays—and the requirement for a transmitter with effective radiated power (ERP) that exceeded the gigawatt (GW) level (1 GW is equal to 90 dBW, as plotted on Figure S.4).

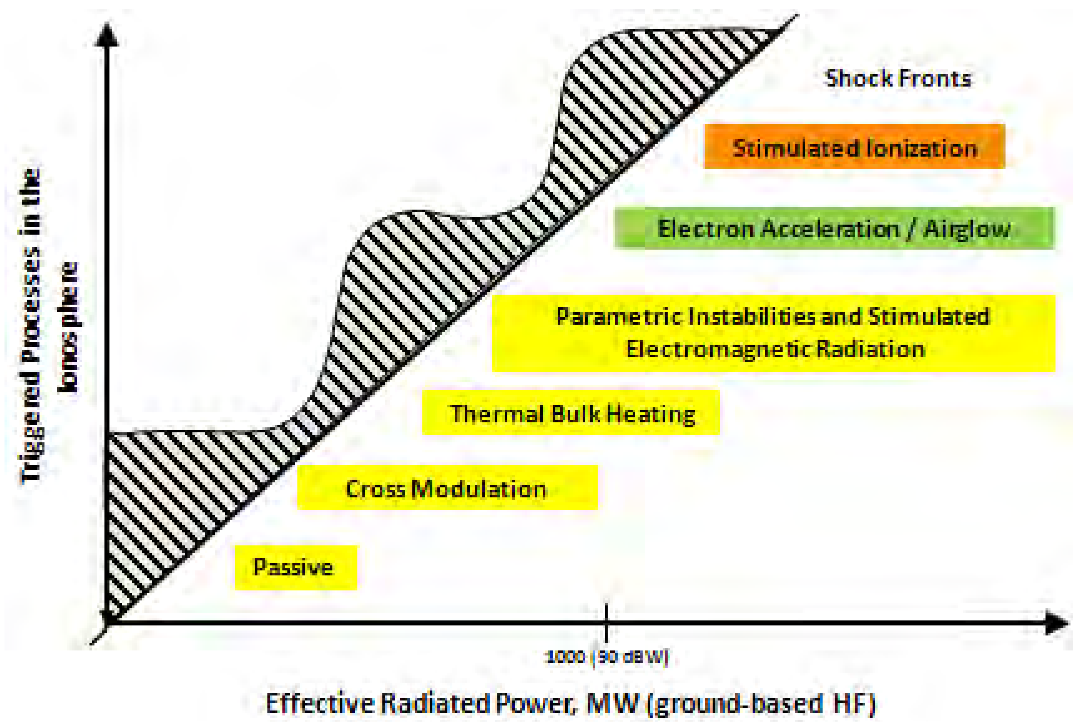

FIGURE S.3 Hierarchy of heater effective radiated power thresholds for excitation of plasma processes in the lower atmosphere. SOURCE: H.C. Carlson, Jr., High-power HF modification: Geophysics, span of EM effects, and energy budget, *Advances in Space Research* 13:15-24, doi:10.1016/0273-1177(93)90046-E, 1993. Courtesy of Herbert Carlson and COSPAR.

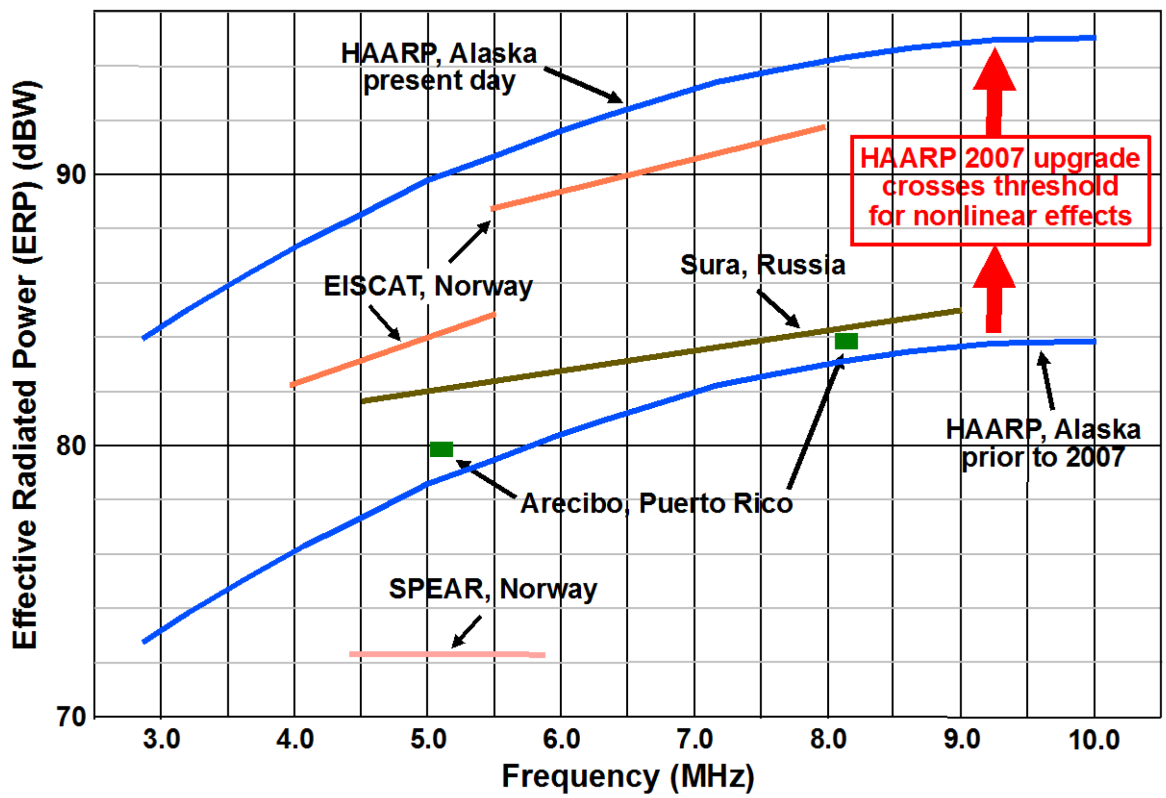

FIGURE S.4 Effective radiated power (ERP) versus frequency for high-frequency heating facilities. The performance of HAARP facility before the upgrade in 2007, which enabled the recent “unique and ground-breaking” results described in this report, is also indicated. The Arecibo facility is under construction and will come on line in 2014. NOTE: EISCAT, European Incoherent Scatter Scientific Association; SPEAR, Space Plasma Exploration by Active Radar. SOURCE: E. Kennedy, Naval Research Laboratory, “Heating Facilities Update: High-Frequency Active Auroral Research Program (HAARP),” 4th Radio Frequency (RF) Ionospheric Interactions Workshop, Santa Fe, New Mexico, April 19-22, 1998.

Recent experiments at HAARP, some only possible since 2007 when the facility was completed and operation at the full design power became possible, have resulted in observations of phenomena that multiple participants characterized as new and exciting:

- The creation of artificially ionized layers descending from near the F-peak to altitudes close to 150 km;
- The capability of sustaining high-density plasma clouds in the F-region for more than 3 h, ending only when the heater was turned off;
- Virtual antenna ULF/ELF generation with modulated F-region heating without requiring the presence of the natural electrojet;
- Triggered emissions by injection of ELF/VLF waves in the radiation belts; and
- Generation of very small size irregularities capable of enhancing total electron concentration (TEC) and affecting gigahertz (GHz) radio wave propagation.

Although a host of new phenomena were discovered using the new capabilities of the HAARP heater, a comprehensive understanding, including how the new phenomena would scale, was said by some participants to have been hindered by the following: (1) lack of proper incoherent scatter radar (ISR) radar diagnostics and (2) insufficient diagnostic satellite overflight coverage following the

termination of the DEMETER[8] satellite mission. During the workshop, Dennis Papadopoulos noted that the large number of satellite missions with excellent diagnostic instruments, including the Van Allen Probes, the Canadian e-POP/CASSIOPE,[9] the Russian Resonance,[10] the Air Force DSX,[11] and the Japanese ERG,[12] as well as several CubeSat and microsatellite missions of opportunity, is expected to resolve the latter impediment during the next few years. Other participants noted that the relocation of PFISR to Gakona (discussed below) would be of great help in addressing the former. An ISR had been part of an initial proposed design for the HAARP facility, but it was not funded; [13] its addition was also advocated in an influential 2002 report of a study conducted by the director of DARPA.[14]

Papadopoulos asserted that the unique combination of the Russian Resonance mission, discussed more extensively in the Chapter 3 section "Dynamics of the Radiation Belts," in combination with HAARP and a modern ISR, would produce "transformational science" because this combination would effectively constitute a unique type of experimental plasma physics laboratory in space. He noted that the unique magneto-synchronous orbits of the twin microsatellites would allow them to stay on the HAARP magnetic field lines, perform measurements, and guide HAARP operational modes over times in excess of 30 minutes. Further, he noted that the combination of ISR and satellite diagnostics, along with active HF ionosphere research, has important strategic implications in the overall structure and connections of space science. Papadopoulos stated that the ISR provides an intimate connection between passive and active ionosphere-thermosphere-magnetosphere (ITM) research, while the satellite diagnostics provide a similar connection between active ionosphere and magnetosphere/radiation belt research.

While emphasis at the workshop was placed on HAARP, the major contributions provided by the EISCAT (European Incoherent Scatter Scientific Association) heater facility at Tromsø, Norway, were also noted. In particular, as noted by Brett Isham, EISCAT's lower effective radiated power and more

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[8] DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) was a microsatellite mission of the French space agency CNES that ended in late 2010. See http://smsc.cnes.fr/DEMETER/.

[9] The Institute for Space Imaging Science at the University of Calgary is leading the operation of the Enhanced Polar Outflow Probe (e-POP), a scientific payload for CASSIOPE, a small satellite mission from the Canadian Space Agency that was launched successfully on September 29, 2013. (In addition to e-POP, CASSIOPE carries a commercial communications payload, CASCADE. The acronym CASSIOPE is derived from "Cascade, SmallSat and Ionospheric Polar Explorer.") The Institute for Space Imaging has links for further information at http://mertensiana.phys.ucalgary.ca/.

[10] "Resonance is a Russian space mission consisting of four identical spacecraft in specific Earth orbits, within the same magnetic flux tube for a certain period of time. The launch is scheduled for 2015. The aim of the mission is the investigation of wave-particle interactions and plasma dynamics in the inner magnetosphere of Earth, with the focus on phenomena occurring along the same field line and within the very same flux tube of the Earth's magnetic field. Among a variety of instruments and probes, several low- and high-frequency electric sensors will be onboard that can be used for simultaneous remote sensing and in situ measurements" (Institut für Weltraumforschung website, at http://www.iwf.oeaw.ac.at/en/research/near-earth-space/resonance/). See also http://www.iki.rssi.ru/people/z_et_al.pdf.

[11] "The Air Force Research Laboratory has developed the Demonstration and Science Experiments (DSX) to research technologies needed to significantly advance the capability to operate spacecraft in the harsh radiation environment of medium Earth orbits (MEO)" (Schoenberg et al., 2006). See also Scherbarth et al. (2009). Another mission of interest that may overlap with DSX, noted during the review of this workshop summary, is TARANIS (Tool for the Analysis of Radiations from Lightnings and Sprites), a French-led mission scheduled to be ready for launch in late 2015 (see http://smsc.cnes.fr/TARANIS/).

[12] "The ERG (Energization and Radiation in Geospace) project is a mission to elucidate acceleration and loss mechanisms of relativistic electrons around Earth during geospace storms. The project consists of the ERG satellite, ground-based network observations, and simulation/modeling/theory teams" (ERG Science Center at STEL, Nagoya University, available at http://ergsc.stelab.nagoya-u.ac.jp/).

[13] Joint Services Program Plans and Activities, Air Force Geophysics Laboratory, and Navy Office of Naval Research (1990).

[14] Anthony Tether, Director of DARPA and Chair, Committee on Future Direction of HAARP, presentation summarizing this report's findings, 2002, available at http://spp.astro.umd.edu/SpaceWebProj/Tether_Panel.ppt.

limited operational flexibility as compared to HAARP was more than made up for by its excellent radar diagnostics. Indeed, various participants cited the wealth of EISCAT studies of irregularities, stimulated electromagnetic radio emissions,[15] optical emissions, and electrojet-modulation-based virtual antennas at ULF, ELF, and VLF frequencies as evidence that enhanced diagnostics at HAARP would allow the facility to quickly move into addressing the next level of challenges in active modification research.

2. What are the fundamental research areas in ITM science that can be addressed using high-power HF-band transmitters?

Studies of the nonlinear interaction of HF radio waves with the ionosphere using recently developed powerful and agile ionospheric heaters, such as the EISCAT heater and more recently the completed HAARP heater, have resulted in the development of novel techniques that workshop presenters, including Herbert Carlson, described as potentially transformational in their implications for understanding ITM regions and their coupling. According to Carlson and other participants familiar with recent active experiments, science areas impacted by the novel recent discoveries at EISCAT and HAARP include the following:

- *Radio science.* A key tool in this research area is the development of artificial plasma layers (APLs). By controlling the location, duration, and properties of the APLs, researchers can conduct studies of guidance, redirection, enhancement, and degrading of trans-ionospheric communications links at HF, VHF, and UHF frequencies and the effects of enhanced TEC and artificial ionospheric turbulence on Global Positioning System (GPS) signals and mitigation of over-the-horizon radar signals in the Arctic.
- *Mesosphere-thermosphere diagnostics.* Several diagnostic techniques involving active HF heating have been tested and verified recently. These include (1) artificial periodic irregularities (APIs) formed by the interference of the incoming and reflected HF waves to diagnose the neutral density and temperature of the D and E regions; (2) optical emissions due to F-region heating for measurements of the neutral density, composition, drag, neutral diffusion, and thermospheric wind velocity in the F-region; and (3) probing of the properties of polar mesospheric clouds.
- *Space weather.* The location of the HAARP facility was cited as particularly favorable in comparison to other heater locations because under quiet conditions, it maps into the plasmasphere; during substorms, it is located inside the subauroral region and is mapped near the plasma pause; and during storms, it is inside the auroral zone. As a result, it was asserted that high-power HF heating experiments can advance understanding of space weather processes in all relevant geospace regions. These processes include (1) subauroral polarization stream (SAPS)/subauroral ion drift (SAID)-related outflows;[16] (2) high electron temperature excited chemistry and density troughs; and (3) high-temperature ion-outflow-created atmospheric gravity waves.
- *Magnetosphere-radiation belts.* Dennis Papadopoulos stated that the most important development for this topic is the concept of "virtual antennas," which allows injection of whistler, shear Alfvén, and magnetosonic waves in the magnetosphere and the radiation belts and ULF/ELF/VLF waves in the Earth-ionosphere waveguide. Papadopoulos noted that measurements of the propagation and interaction of these waves with the plasma and energetic radiation belt particles allow for comprehensive cause-and-effect studies of critical processes, such as the physics of triggered emissions and chorus, propagation characteristics, attenuation rates and mode conversion effects of whistler and Alfvén waves, pitch angle scattering rates of trapped particles on whistler, Alfvén and EMIC waves, excitation of field line resonances, and properties of ionospheric and magnetospheric waveguides and resonators. An additional task that can be achieved with the use of virtual antennas is the assessment of radiation belt remediation systems that will be required in case of a Carrington event and deliberate or accidental high-altitude nuclear explosion.

[15] For further discussion, see, for example, Leyser (2001).
[16] See Foster and Burke (2002).

- *HAARP as 110 MW/acre radar*. In his presentation to the workshop, Todd Pedersen described a new capability of HAARP he thought particularly exciting: operation as an HF radar. With the addition of a receiver, HAARP could be used for ionospheric imaging (via incoherent and coherent scatter); plasmaspheric, magnetospheric, and solar corona/wind sounding; and planetary subsurface measurements, while retaining its capability as an active HF heater.[17]

3. What are the key diagnostic instruments needed in conjunction with high-power, HF-band transmitters to address questions 1 and 2?

Many participants stated that in addition to its existing diagnostic instrumentation, addressing questions 1 and 2 will require the addition of an ISR at the HAARP site. Some participants also noted the need for extensive satellite heater over-flight coverage by properly instrumented satellites. Further, some participants noted that important diagnostic benefits to active experiments as well as to passive diagnostics can be derived by use of the API technique, which is described in more detail in Chapter 1 of this report.

- Numerous participants, including Richard Behnke, Robert Robinson, Robert McCoy, Dennis Papadopoulos, Paul Bernhardt, Todd Pedersen, Herbert Carlson, David Hysell, and Brett Isham, stated that moving an ISR to the HAARP site would provide critical diagnostic information that would help resolve physics-related issues involving ionosphere-thermosphere diagnostics, the physics of artificial ionization, and the details of virtual antenna operation.
- Other participants noted that HAARP could be operated as a radar by upgrading the existing radar receiver to an imaging array. This can be accomplished by using a few hundred antennas spread out over 100 to 1,000 m or more, co-located or remote from the HAARP site, at a cost—estimated at the workshop by Todd Pedersen by analogy to new low-frequency arrays such as the Long Wavelength Array (LWA) near the Very Large Array (VLA) in New Mexico—to be approximately $1 million. This addition would create unique new capabilities and enable novel research for plasmasphere, magnetosphere, and heliosphere research in addition to active or passive ionosphere studies.
- Papadopoulos stated that spacecraft overflight of HAARP in magneto-synchronous satellite orbits, such as the ones planned for the Resonance mission, promise to revolutionize the utility of HF heaters for understanding the physics of the radiation belts; they would also be a critical complement to the science derived by the Van Allen Probes and other radiation belt missions.
- Pedersen and others noted that the API technique requires the ionospheric modification facility to have at least a modest receive capability, which could be accomplished by using a specialized HF receiver and antenna. According to Pedersen, an ionosonde-class antenna would be sufficient at a minimum. Both the receiver and antenna should accommodate dual polarizations. The heater itself must be configured to use either a pulsed or pulse-code mode. An imaging array of the kind described above would be ideal for API research.

4. Are there emerging science questions that might benefit from active ionospheric experiments in the subauroral zone?

The subauroral zone is the region where SAPS, the outstanding feature of the perturbed plasmasphere, occurs. As such, it is an area of great interest vis-à-vis space weather. It was argued by Dennis Papadopoulos and others that with its location in the subauroral zone during weak and moderate substorms, investigations conducted with the HAARP facility can advance understanding of key space weather processes in subauroral geospace, as well as mimic aspects of substorm dynamics, by inducing

[17] In his presentation, Pedersen stated that with respect to applications, "What do I do with an ionospheric heater?" may be the wrong question, instead, he believes the right question is, "What could I do with a 110 MW-acre *radar* in the 3 to 10 MHz range?" Pedersen asserted that an imaging receive array could provide "huge" new capability for little cost and that there would be numerous unique possibilities for plasmasphere, magnetosphere, and heliosphere research, in addition to active or passive ionosphere studies, all while still having the ionospheric heating capabilities.

effects similar to the ones created during natural events. Such HF-driven effects were said to include (1) injection of artificially created gravity waves, (2) joule heating and conductivity modification of the D/E region, (3) thermospheric heating and associated satellite drag effects, and (4) ion outflows and duct formation.

5. What operating parameters (e.g., power and transmission frequency) are needed to address questions 1-4?

While some participants noted radar applications that could benefit from access to higher HF frequencies, none mentioned difficulties in addressing questions 1-4 employing HAARP with its currently available capabilities.

6. Are there ways to combine similar facilities (e.g., EISCAT, Arecibo) to perform global ionospheric science?

No direct opportunities were noted during discussions at the workshop. However, a participant observed that data acquired at each location can be compared to develop useful "scaling laws." For example, comparing the input/response at the high-latitude ionosphere at HAARP to that of the lower-mid-latitude ionosphere at Arecibo was said to allow illumination of the critical role of Earth's magnetic field for accessing fundamentally different plasma instability processes and dramatically enhanced efficiency of energy deposition for injection at high latitudes.

Larry Paxton noted that forcing from the lower atmosphere is thought to account for perhaps 20 to 30 percent of the observed variability in the upper atmosphere. This led to a discussion of the potential to operate heaters at a variety of latitudes to help in understanding how the global atmospheric system responds to different types of energy inputs. Reflecting a theme heard in different contexts throughout the workshop, one participant envisioned important advances in magnetospheric physics coming from the use of a combination of techniques: HF heaters located at a wide range of latitudes, the associated ISRs, and having satellite coverage of the latitudes where the HF facilities are located.

7. What research opportunities might arise from the relocation of the advanced modular incoherent scatter radar (AMISR) from the Poker Flat Research Facility in Poker Flat, Alaska, to Gakona, Alaska, the location of the HAARP facility?

An ISR was included in early HAARP proposals as a way "to provide the means to monitor such background plasma conditions as electron densities, electron and ion temperatures, and electric fields, all as a function of altitude."[18] At the workshop, a participant noted that such diagnostic information is critical for a quantitative understanding of the physics controlling artificially ionized layers, virtual antenna generation, triggered emissions, field-aligned striations, and for predicting the behavior and scaling of these phenomena at facilities located at other latitudes. In addition, an ISR was said to provide the means for "closely examining the generation of plasma turbulence and the acceleration of electrons to high energies in the ionosphere by HF heating." [19]A workshop participant noted that over the years of operating HAARP without an ISR, researchers had developed proxies for estimating state parameters. However, these proxies have not been validated, and it was said that even temporarily relocating PFISR to Gakona would help validate the methodologies that have been developed in the absence of an ISR.

Specifically, according to several participants, moving PFISR to the HAARP site is expected to

- Validate conclusions made using proxy techniques that were developed in the absence of an ISR and used to infer, for example, electron and ion temperatures and densities and drifts, all of which can be directly measured using the ISR technique.

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[18] See Joint Services Program Plans and Activities, Air Force Geophysics Laboratory, and Navy Office of Naval Research (1990).

[19] See Joint Services Program Plans and Activities, Air Force Geophysics Laboratory, and Navy Office of Naval Research (1990).

- Allow the detailed study of Langmuir and other turbulence processes, as has been done with great scientific success at EISCAT and Arecibo.
- Dramatically improve the current limited understanding of processes occurring in the horizontal directions above the HAARP heater and answer the question, Are the recently created artificial ionospheric layers actual layers, or are they more like filaments or patches?"
- Contribute to the introduction of a new methodology in ITM research by creating a facility that brings together distinct research communities and experimental techniques. The new methodology would combine traditional passive observational techniques, currently used by the upper atmosphere-ionosphere and magnetosphere communities, with active experimentation that uses geospace as an open laboratory for active cause-and-effect experimentation. According to some participants, the result would be important advances in scientific understanding of

  — The physics of Earth's radiation belts.
  — The role of ionosphere conductivity in atmosphere-ionosphere-magnetosphere coupling.
  — The dynamics of ionosphere-thermosphere coupling.

The benefit of the ISR technique, with its ability to directly measure the key fundamental plasma parameters without disturbing the ambient plasma, was cited repeatedly at the workshop. One participant stated that an ISR at HAARP would benefit all experimental activity, as evidenced by the three HF facilities that have ISRs: EISCAT, Arecibo, and SPEAR (Space Plasma Exploration by Active Radar),[20] all of which were said to nearly always run their HF experiments taking full and productive advantage of the possibility of supporting measurements by the co-located ISRs.

As noted by NSF representatives at the workshop, additional value to HAARP is expected to come via the involvement of the community of scientists that currently use the PFISR radar at Poker Flat, Alaska, the ISR that they would like to be moved and utilized at HAARP. The scientific potential of this combination was discussed at the workshop, and several participants commented on both the synergy of an ISR and HAARP and the value of bringing together the traditionally separated communities that perform strictly passive observations and those who include active perturbations in their research. Herbert Carlson stated that the involvement of NSF, brought in via the inclusion of the current PFISR radar, would also contribute to opening HAARP up to additional communities of researchers new to the possibilities and potentials of using active HF techniques.[21]

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[20] SPEAR is an HF heater located above the Arctic Circle at 78.15°N in Svalbard, Norway.

[21] This point was also made in the 2013 National Research Council decadal survey *Solar and Space Physics: A Science for a Technological Society* (NRC, 2013). The survey report includes chapters written by each of the three study panels that reported to the overall steerting committee. The survey's AIMI (atmospheric-ionospheric-magnetospheric interactions) panel included the following: "The DOD operates and maintains the world's largest ionospheric modification facility, HAARP, near Gakona, Alaska. HAARP is not collocated with an incoherent scatter radar, and so its full potential has not been realized since the phenomena it creates cannot be fully diagnosed . . . . Another ionospheric modification facility is under construction at the Arecibo Radio Observatory. While this facility will be modest in power compared to HAARP, its collocation with Arecibo, the world's most sensitive incoherent scatter radar, raises the prospect of discovery science in the areas of artificial and naturally occurring ionospheric phenomena.The Arecibo heater came about through close collaboration between DOD and NSF. The AIMI panel regards this kind of interagency cooperation as a model to be followed for the utilization of existing ionospheric modification facilities as well as the planning and development of new ones" (p. 201).

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Introduction

EXPLORING GEOSPACE USING HIGH-FREQUENCY HEATING: NOVEL TECHNIQUES

Traditionally, experimental geospace research, including probing of the atmosphere, the ionosphere, and the magnetosphere (AIM), has been conducted passively (i.e., no controlled input/response capability) using instruments located on the ground or on satellites. From this research has come the recognition that most of the individual processes that underlie the upper atmosphere and ionosphere's structure and dynamics are coupled and difficult to study in isolation, especially when it is not possible to uniquely identify the driver of a particular process.

Research conducted by the ionospheric modifications (IM) community—a community that uses high-frequency (HF) transmitters to inject energy in the ionosphere and measure its effects using ground- and space-based diagnostics—is focused on understanding the interaction of radio waves with the ionospheric plasma, the local consequences of heating in the ionosphere, and studies of nonlinear plasma physics processes. Some workshop participants noted that while the IM and the AIM community share many scientific goals and require similar ground and space instrumentation, their interactions have heretofore been sporadic.

The guiding principle of the recently completed decadal survey in solar and space physics (NRC, 2013) was that transformational scientific progress is required in order to study the Sun, Earth, and the heliosphere as a coupled system. It was noted at the workshop that the natural processes by which geomagnetic events affect this complex system are very similar to the kind of experiments that can be performed with ionospheric modification, such as those done at the High Frequency Active Auroral Research Program (HAARP; see Box 1.1). Such modifications can be used to perform controlled experiments to better understand natural processes in what is otherwise a very complex system, a point emphasized by numerous participants. Heating can also probe regions of parameter space that are unattainable with other techniques. In addition to perturbing the natural system, several participants noted that active experiments can address universal processes in plasma physics, essentially creating what was described as a cosmic plasma laboratory without walls.

Studies of the nonlinear interaction of HF radio waves with the ionosphere using recently developed powerful and agile ionospheric heaters, such as the EISCAT (European Incoherent Scatter Scientific Association) heater and more recently the completed HAARP heater (Appendix E), have resulted in the development of novel techniques that some participants described as transformational in their implications for understanding the physics of ionosphere-thermosphere-magnetosphere (ITM) regions and their coupling. Among the areas of research highlighted by some participants are the following:

- Mesosphere-thermosphere diagnostics;
- Artificial plasma layers (APLs) at altitudes between the F peak and 150 km and associated optical emissions;

BOX 1.1
Ionospheric Heaters Mimic Natural Processes

Solar radiation interacting with Earth's atmosphere creates the ionosphere, the shell of ionized plasma enveloping Earth, the discovery of which led to long-range wireless communication. Participants at the workshop, including Jade Morton, John Foster, and Anthea Coster, described research to achieve a fuller understanding of the ionosphere that is motivated by the increasing modern reliance on satellite resources, such as the Global Positioning System (GPS), and concerns about space weather. Plasma instabilities within the global ionosphere, especially during major magnetic storms, disrupt reliable access to satellite communications, GPS navigation, and other civilian, commercial, and defense national satellite resources.

The physics of the production of Earth's bulk ionosphere is straightforward: Solar radiation energy breaks electrons loose from neutral particles in the upper atmosphere, and conservation of momentum makes the low-mass electrons separate at vastly higher velocity than the ions left behind, thereby carrying almost all the initial kinetic energy. Recently completed high-power, high-frequency (HF) research facilities like the High Frequency Active Auroral Research Program (HAARP) can deliver radio-frequency energy densities comparable to that from the Sun, and through wave-particle interactions, found universally in plasmas throughout space (local, interplanetary, intergalactic), can break electrons loose from neutral species at a rate comparable to that by the Sun. From this point on, the physics (whether ionization by solar photon or radio-frequency radiation) is the same as for natural energy flows. Hence, there is great interest in applications for space science, as described by many workshop participants and summarized here.

At the workshop, Herbert Carlson noted that a great qualitative advantage of energy deposition from ground-based research facilities is that for the first time it is now possible to conduct controlled experiments, versus simply watching and waiting for the Sun to perturb space and then attempting to learn from studying its response. Carlson and other participants who are active users of heaters emphasized the value of being able for the first time to carry out controlled input-response experiments.

In addition, many participants noted that these new capabilities enable exploration of the basic underlying nature of a wide range of properties of the neutral and ionized matter forming our environment. As summarized by Carlson, active experiments provide scientists with a qualitatively new "laboratory in the sky," to excite input-response discoveries that span over 12 orders of magnitude—a million million-fold—of scale size. He further noted that this capability enables wide-ranging studies, such as the flow of energy in matter, cascading in excited states of atoms and molecules; ionizing matter to probe aspects of the very nature of particle, collective-gas, and wave-particle energy exchange; and exploring fundamental plasma processes, which bear directly on attempts to realize controlled plasma fusion. All of the above is also highly relevant to understanding the geospace response to solar storms and the development of space weather near Earth.

In his presentation to the workshop, Carlson noted the decade of HAARP construction coincided with the development of a research community that has learned how to control and use energy deposition in neutral and plasma species. As Carlson put it, both the facility and the community now stand ready to explore and discover new and fundamental physical phenomena, some not yet imagined, of fundamental importance to both civilian/industrial and defense users. He added that additional diagnostic capabilities, especially those that will be provided by the transfer to Gakona of the Poker Flat Incoherent Scatter Radar, make this even more likely.

- Generation and injection into the Earth-ionosphere waveguide (EIW) and into the magnetosphere electromagnetic (EM) waves at ULF/ELF/VLF frequencies (ultralow frequency/extremely

low frequency/very low frequency) by modulated HF heating of the ionosphere, also known as "virtual antennae;"

- Generation of artificial ionospheric turbulence (AIT) that increases the level of scintillation and affects the propagation of trans-ionospheric electromagnetic signals, such as the Global Positioning System (GPS), HF communications, and space radar; and
- Generation of strong plasma outflows and associated field aligned ducts that focus HF and guide VLF signals.

Mesosphere-Ionosphere Diagnostics

In presentations and discussions at the workshop, a number of ionospheric modification techniques were cited as providing diagnostic information about the mesosphere/ionosphere. The following list includes techniques noted by one or more participants.

- The study of artificial periodic irregularities (APIs) were said to be a powerful technique for determining electron and neutral densities and temperature. APIs are formed in the lower ionosphere by a standing wave due to the interference of incoming and reflected HF radio waves. Probing waves scattered by those irregularities carry information about ambient electron density and vertical velocity. In addition, the neutral density and temperature can be deduced by measuring the temporal relaxation of the irregularities (and finding the rate of ambipolar diffusion).
- Polar mesospheric summer echoes (PMSEs) were said to be an indicator of polar mesospheric clouds (PMCs). PMCs have been detected at an increasing rate at lower and lower latitudes and may be linked to global climate change (Thomas et al., 2010). PMCs are composed of dust grains (aerosols) of submicron size at the altitude 80 to 90 km. These dust particles are charged by the attachment of free ionospheric plasma particles and photoemission of electrons by solar radiation, which enables interactions with HF waves. One workshop participant noted that recent observations of PMSE modulations created using the EISCAT heating facility could help to deduce mean grain size, dust density, and photoemission rates from PMSE temporal variations.
- Some participants discussed using HF-induced optical emissions to measure neutral densities at altitudes between 200 and 350 km (F-region). The decay rate of an excited oxygen optical emission at 630 nm, $O(^1D)$, is determined by the number density and composition of the neutral atmosphere. Thus, by detecting the optical decay rate at different altitudes, the altitude profile of the neutral density can be deduced, which is of special interest in determining the drag force in the ionosphere.
- The analysis of optical emissions from quasi-steady-state clouds excited by high-power radio waves were another diagnostic technique discussed at the workshop. The shape of the cloud is determined by neutral diffusion and thermospheric winds. After the HF waves are turned off, the glowing cloud persists long enough that it will expand by diffusion in the neutral atmosphere and move along the direction of the neutral wind. Observations of the cloud shape and the motion immediately after HF power is turned off yield the horizontal components of neutral wind and diffusive flux (Bernhardt et al., 2000). In addition, use of a Fabry-Perot interferometer to measure $O(^1D)$ emissions from the cloud can determine the line-of-sight neutral winds at the altitude of the artificial airglow cloud.

Artificial Plasma Layers

As was explained at the workshop, at low powers, electromagnetic waves propagate in the ionosphere without producing any observable change in the plasma environment. High-power radio waves, on the other hand, reportedly can drive nonlinear processes that yield electrostatic waves that interact with the ambient plasma to accelerate electrons to well above their thermal energies. The energetic electrons collide with neutrals to yield excited species that subsequently radiate as optical

emissions. If the electron energy is high enough, the high-speed electrons can ionize the background neutral gases to yield localized regions of artificial ionization.

The recently demonstrated (Pedersen et al., 2010) capability of HAARP's 3.6-MW transmitter to produce significant artificial plasma in the upper atmosphere was said to open "the door to a new regime in ionospheric radio wave propagation where transmitter-produced plasmas dominate over the natural ionospheric plasma" (p. 1). Eventually, some participants speculated, it may be possible to employ this technique as an active component of communications, radar, and other systems. Imaging of artificial airglow from these "layers" allows their existence, location, and dynamics to be precisely identified; depending on their location, they can also affect satellite communications and navigation.

Ionospheric Generation of ULF/ELF/VLF Waves

At ULF/ELF/VLF frequencies, traditional dipole antennas are extremely inefficient and require very long wires. However, as noted repeatedly at the workshop, it is possible to generate these frequencies using a virtual ionospheric antenna through ionospheric modification techniques. There are two techniques for generating such waves. The first, known as current modulation, requires the presence of an electrojet current above the HF heater, and thus its use is restricted to high-latitude transmitters (currently, there are currently no HF heating facilities under the equatorial electrojet), and its availability and strength are controlled by the strength of the electrojet. Experiments to date have demonstrated generation of frequencies up to 20 kHz, with the upper frequency limited by the electron temperature relaxation rate at the generation altitude. The generated waves are then injected as EM waves into the EIW and as whistler and shear Alfvén waves (SAW) into the radiation belts (Rietveld et al., 1984, 1989; Barr, 1998; Papadopoulos et al., 1990, 2005). Modulated heating of the D/E-region electrons modulates the plasma conductivity generating a virtual antenna at altitudes between 70 and 85 km.

A recently developed alternative technique mentioned at the workshop—ionospheric current drive (ICD; Papadopoulos et al., 2011a,b) does not require the presence of electrojet. As a result, it can be employed at non-electrojet regions with heaters, such as those located at Arecibo and Sura, and it is available to HAARP and EISCAT during conditions when the electrojet is weak or absent. ICD relies on the generation of a diamagnetic current during F-region heating that disappears when the heater is off. Generation of ULF/ELF/VLF waves through HF techniques was discussed at the workshop in connection with applications such as underwater communications and wave injection into the radiation belts.

HAARP IS AT A CROSSROADS

The HAARP program was initiated in 1990 by congressional action. Congress followed the recommendation of several scientific panels that there was an urgent need for a U.S.-based "world-leading" experimental facility with a heater based on modern electronic phased-array beam steering with wide transmitter frequency coverage and power exceeding theoretical thresholds for triggering strongly nonlinear processes, which was supported by an extensive complement of diagnostic instruments. The facility was completed and achieved its full design power in 2007 and has produced, according to several participants, a number of scientific firsts and breakthrough physics, in addition to being instrumental in training future workers in radio science and space-related disciplines. A dedicated site technical staff (currently at Marsh Creek Ltd.) created powerful software and hardware techniques to operate and maintain this antenna, which participants were told is now at the peak of its performance.[1]

According to several workshop participants, the scientists and engineers running experiments at HAARP have been handicapped by the lack of a key diagnostic instrument, namely an incoherent scatter

[1] Indeed, there was discussion at the workshop about the vulnerability of HAARP maintenance owing to the consolidation of expertise to a few specific individuals working as private contractors.

radar (ISR). Further, these participants noted that such an instrument is now available, built from the next-generation ISR technology incorporated in AMISR. AMISR's novel modular configuration allows it be relocated with relative ease, thus enabling the study of upper atmospheric activity around the globe. In addition, remote operation and electronic beam steering allow researchers to operate and position the radar beam instantaneously.[2] AMISR radars have so far been constructed in two locations. The first, in Poker Flat, Alaska, known as PFISR, has been completed and is already being used for scientific investigations. The second, the Resolute Bay ISR (RISR) in Nunavut, Canada, has two antennas pointed in complementary directions, the north-directed radar currently operating and the south-directed radar complete but not yet fully operational.

Richard Behnke and Bob Robinson from the National Science Foundation informed the workshop that they would like to move PFISR to the HAARP facility for 1 year (or possibly more) of coordinated experimental campaigns. With HAARP complete as of 2007, and with the potential of the addition of an ISR and other diagnostic instruments, HAARP users at the workshop spoke enthusiastically about new experiments and the potential for new scientific discoveries. At the same time, there was considerable discussion at the workshop regarding the future of the facility, given the Air Force's current plans to wind-down its support and plan for the facility's decommissioning.

HAARP'S UNIQUE CAPABILITIES

HAARP is located at 62.39° north latitude, 145.15° west longitude, which translates to 63.09° north magnetic latitude and 92.44° west magnetic longitude. At this magnetic latitude, the facility can observe regions rich with geophysical phenomena. Under nominal geomagnetic conditions, the region is between the mid-latitudes and auroral zone and is magnetically conjugate to a region of the magnetosphere close to the Van Allen radiation belts. As geomagnetic conditions vary, so does the conjugate position. Under moderately active conditions, HAARP can be in the auroral zone, or even in the polar cap at higher levels of activity. In addition, it is reasonably isolated from populated areas, which results in very dark skies. Hence, the facility has great potential as a location for an observatory (Figure 1.1).

The HAARP ionospheric research instrument (IRI) is physically capable of transmitting any frequency between 2.8 and 10 MHz with an instantaneous bandwidth of at least 200 kHz. This frequency range is the broadest of any heating facility, going both lower and higher than all others. The low end of the band is just below twice the electron gyro frequency in the ionosphere over HAARP. It is the only heating facility that is able to transmit below this important value. The ability to transmit as high as 10 MHz ensures that the facility can probe into the F-region even under high plasma density conditions. Such a broad range allows operation throughout a complete solar cycle.

Because each of the HAARP transmitters can generate from 10 W to 10 kW, the total transmitted power can range from 3,600 W to 3.6 MW, while maintaining a consistent antenna pattern. As already noted, the HAARP antenna consists of an array of 180 crossed dipoles, which are arranged in a 12 by 15 rectangular grid and are phased to provide steering. At the low end of the frequency band (2.8 MHz), the array main lobe beam width is about 15°, while at the upper end of the band (10 MHz), it is about 5°. Below about 5.8 MHz, the antenna beam can be steered anywhere in the sky without the possibility of grating lobes. The beam can be repositioned within about 15 μs, which means that the beam can be swept in a nearly continuous motion across an area, or it can be stepped from place to place almost instantly. The transmitter has great flexibility in modulations, including AM, FM, phase, pulse, and any signal that can be represented in a ".wav" file.

[2] Advanced Modular Incoherent Scatter Radar, AMISR Overview, available at http://amisr.com/amisr/about/amisr-overview/, accessed September 4, 2013.

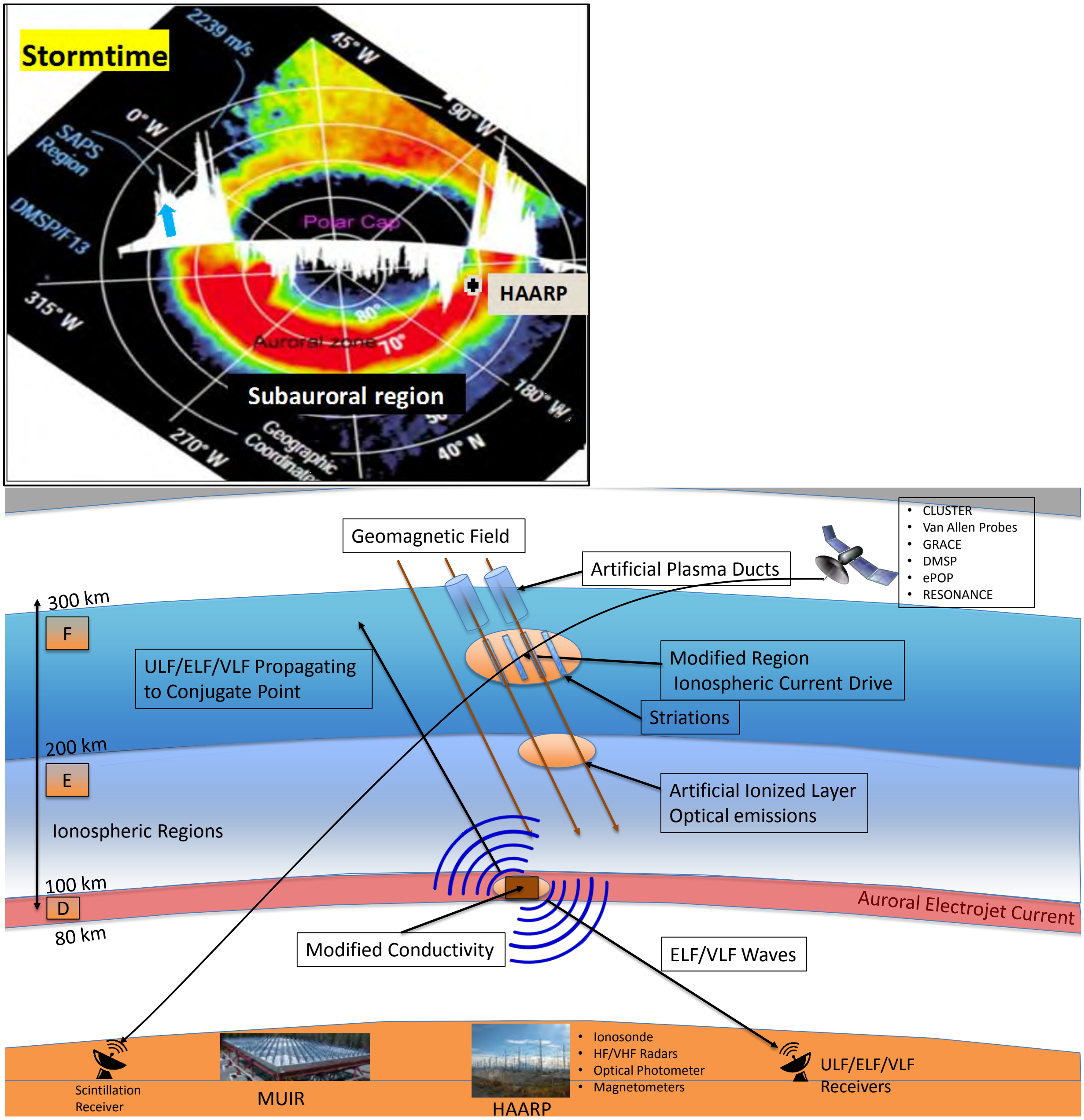

FIGURE 1.1 HAARP has a privileged location that allows for conditions that cover critical geospace phenomena. It is within the auroral zone at storm times, mapped in the plasmasphere during quiet times, and in the subauroral region during substorms. SOURCE: *Top:* E. Mishin, Air Force Research Laboratory, "Using HAARP to Better Understand Space Weather," presentation to the Committee on the Role of High-Power, High-Frequency-Band Transmitters in Advancing Ionospheric/Thermospheric Research: A Workshop, May 2013. Courtesy of Evgeny Mishin. *Bottom:* Courtesy of K. Papadopoulos, University of Maryland.

In addition to the IRI, the HAARP site has a number of diagnostic instruments and facilities to support additional instruments. Some of the diagnostics are owned by the HAARP program (some with an associated principal investigator [PI]), while others are owned by PI institutions and supported by the HAARP program. These diagnostic instruments include magnetometers, riometers, an ionsonde, ultrahigh-frequency (UHF) and very-high-frequency (VHF) radars, optics, GPS scintillation receivers, ELF and VLF receivers, a seismometer, meteorological monitors, an HF receive antenna, and a spectrum monitor.

TABLE 1.1 High-Frequency Ionospheric Heating

Name	Platteville	Arecibo	Sura	EISCAT	HAARP	SPEAR
Location	Platteville, Colorado	Arecibo, Puerto Rico	Vasil'sursk, Russia	Tromsø, Norway	Gakona, Alaska	Svalbard, Norway
First opened	1970	1970	1979	1980	1995	2003
Status	Closed in 1975	New facility operating early 2014	Operating	Operating	Temporary closing June 2013	Operating
Years of operation	1970-1975	1970-present	1979-present	1980-present	1995-present	2003-present
Geographic coordinates	40.2 N 104.7 W	18.3 N 66.8 W	59.1 N 46.1 E	69.6 N 19.2 E	62.4 N 145.2 W	78.2 N 16.0 E
Geomagnetic latitude	48.2 N	28.1 N	53.2 N	66.1 N	63.5 N	74.8 N
Geomagnetic dip angle (degrees)	66.9	44.8	73.6	77.6	75.8	82.1
Frequency (MHz)	2.7-10.0	5.1 and 8.175	4.5-9.0	3.9-5.5 5.4-8.0	2.8-10.0	4.45-5.82
Radiated power (MW)	1.4	0.9	0.75	1.2	3.6	0.11
Antenna gain (dB)	19	22 and 26	23-26	22-25 28-31	up to 40	22
Effective radiated power (MW)	100	95 and 240	150-280	180-340 630-1260	up to 3600	17

SOURCE: Adapted from B. Isham, "Overview of HF experiments at EISCAT Tromsø," 13th Radio Frequency (RF) Ionospheric Interactions Workshop, Santa Fe, New Mexico, April 22-25, 2007. Courtesy of B. Isham, Interamerican University, Bayamón, Puerto Rico.

HAARP COMPARED TO OTHER HEATERS

Table 1.1 and Figure 1.2 display some of the technical characteristics of HAARP compared with other HF facilities currently operating, or soon to be operational, and with the original HF facility in Platteville, Colorado. HAARP has a frequency band equaled only by the original transmitter in Plateville and a transmitted power density 36 times that of Platteville and three times that of the high-power array at EISCAT. This capability, unique to the HAARP heater, allows for the generation of artificial ionization layers. Not apparent, however, in Table 1.1 and Figure 1.2 are HAARP's extremely fast and flexible beam-forming and beam-pointing capabilities, which enable many unique experiments discussed elsewhere in the text and the many instruments available at HAARP, with the notable exception being the absence of an ISR such as the powerful and capable ISRs located at Arecibo, EISCAT, and SPEAR.

Table 1.1 and Figure 1.2 make clear that HAARP represents the culmination of achievement in HF ionospheric heaters. It has already been noted that as the HF power delivered to the ionosphere increases, the response of the geophysical environment changes discontinuously,[3] thus indicating the

[3] See Joint Services Program Plans and Activities, Air Force Geophysics Laboratory, and Navy Office of Naval Research (1990).

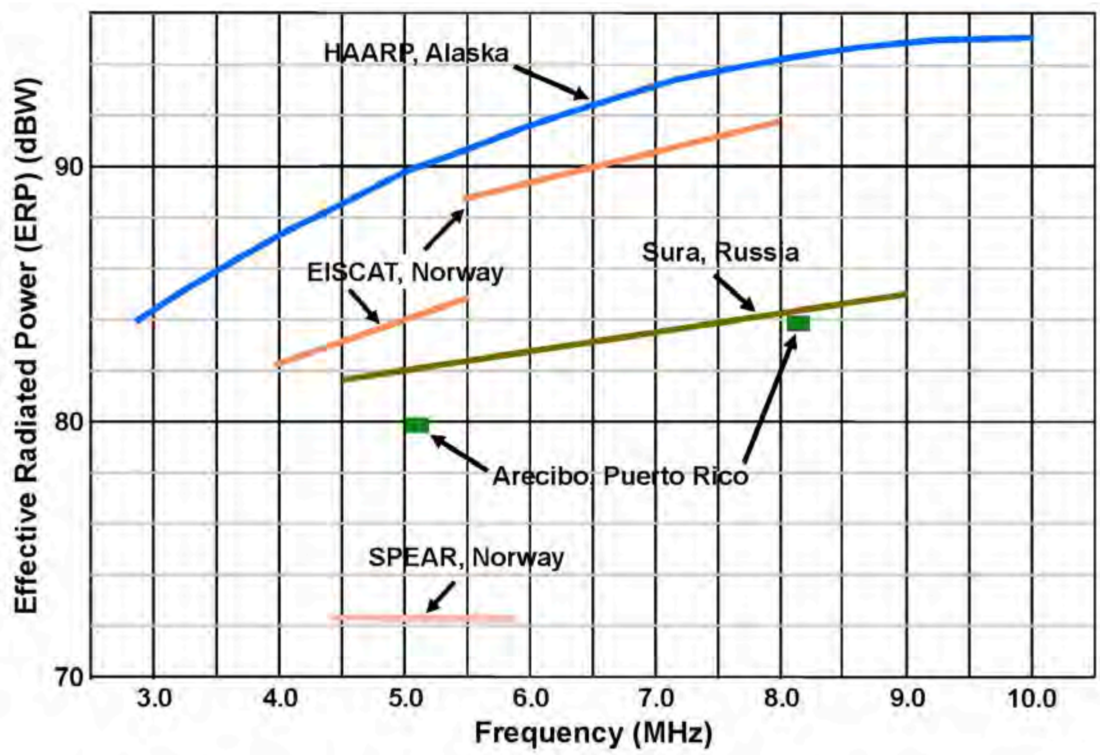

FIGURE 1.2 Effective radiated power versus frequency for current high-frequency heating facilities. The Arecibo facility is under construction and will come on line in 2014. NOTE: 1 GW is equal to 90 dBW. SOURCE: E. Kennedy, Naval Research Laboratory, "Heating facilities update: High-frequency Active Auroral Research Program (HAARP)," 4th Radio Frequency (RF) Ionospheric Interactions Workshop, Santa Fe, New Mexico, April 19-22, 1998.

presence of thresholds (see Figure S.3 in the Summary). Scientists do not know what thresholds may lay ahead, but some participants asserted that HAARP offers the best opportunity to discover as well as to explore new fundamental physics and to unearth opportunities for new systems development. In making this claim, it was noted that while HAARP's "first light" came in 1995, its operation at full power began only in the past few years. In its first experiment at full power, the threshold for ionospheric production was exceeded. It was further asserted that when the new Arecibo facility begins its expected operation in 2014, it will, with HAARP, enable a new surge of exploration of comparative instability processes, utilizing known major latitude dependencies.

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2

Mesosphere, Thermosphere, and Ionosphere

Presentations and discussions at the workshop highlighted the particular potential of ionospheric modification experiments to advance understanding of the mesosphere-lower thermosphere (MLT) and thermosphere regions of the atmosphere, with which the ionosphere is collocated. It was noted that the state parameters of the neutral gas in this region are difficult to measure with ground-based instruments, and the measurements that are possible are often poorly resolved in range or time, or available only within narrow altitude ranges. In particular, a workshop participant noted that neutral winds and densities in the thermosphere are poorly specified, introducing uncertainty into virtually all lines of theoretical investigation in aeronomy. Moreover, because neutral winds and densities control satellite drag, their poor specification was said to have important operational consequences.

It was noted by a participant that ionospheric modifications can also be used to explore coupling between neutral and charged species, because the radio frequency (RF) directly pumps the electrons, but neutral species are responsible for the subsequent relaxation back to radiative and chemical equilibrium. Further, it was asserted that heating experiments can explore this coupling more systematically and over a broader range of conditions than would be otherwise possible. Plasma-neutral coupling is one of the central themes of the National Science Foundation (NSF) Coupling, Energetic, and Dynamics of Atmospheric Regions (CEDAR) program.

Diagnostics generally monitor how the upper atmosphere responds to both RF heating and to its cessation. Ground-based instruments measure airglow, scattered radio signals, and stimulated radio signals from the modified volume. This information allows estimates of neutral winds, densities, temperatures, composition, plasma drifts, and rates of diffusion and cooling.

RECENT RESEARCH HIGHLIGHTS[1]

Multipolar Diffusion

At the workshop, the utility of ionospheric modification for understanding natural aeronomic processes was said to be exemplified by research into polar mesospheric summer echoes (PMSEs). PMSE refers to coherent radar scatter from thin layers in the polar summer mesosphere where charged dust particles and ice crystals associated with polar mesospheric clouds are present. The echoes arise from fluctuations in electron density driven by neutral atmospheric turbulence. It was noted by a workshop participant that the puzzle of how electron density fluctuations at small scale sizes could be sustained in the presence of ordinary ambipolar diffusion was resolved with the help of heating experiments.

In these experiments, an overshoot in echo intensity was consistently observed after heater turn-off (Havnes et al., 2003; Havnes, 2004). The overshoot led to a belated appreciation of multi-polar diffusion, a fundamental process in multi-component plasmas. Mahmoudian et al. (2011) accounted for

[1] This section includes recent research cited by one or more participants as being particularly noteworthy.

the time history of the echoes by modeling temperature-dependent multipolar diffusion, charging, and recombination processes. According to one workshop participant, the result substantially advanced understanding of mesospheric turbulence, chemistry, and transport.

Sporadic E-Layer Patches

Another example cited at the workshop in which ionospheric modification facilitated discovery science in aeronomy concerns the morphology of sporadic E ionization layers. These layers, which were evident in the earliest days of radio, are known often to be non-blanketing and patchy, but observers note that conventional remote sensing instrumentation affords no easy way to image their horizontal structure. Bernhardt et al. (2003) introduced an imaging method, termed “radio-induced aurora,” or RIA, that combines RF heating with optical imaging.

Paul Bernhardt and others at the workshop discussed how ionospheric modification induces enhanced optical emissions via induced electron impact on neutral species that can be used as a diagnostic of background aeronomic processes. Both thermal and suprathermal processes are believed to be at work, with red-line excitation through direct electron heating and green-line excitation through electron acceleration. The red-line emission has a lower excitation energy and dominates green-line emission at F-region altitudes. Since the red-line emission is collisionally quenched at E-region altitudes, however, the green line dominates there.

RIA involves emitting pump-mode radiation at a frequency below the F-region critical frequency. Where there are no sporadic E-layer patches, the radiation propagates into the F region and produces red-line emissions at the F-region interaction height. Where there are sporadic E-layer patches, however, the pump-mode radiation interacts in the E layer. Not only does this produce gaps or “shadows” in the red-line emissions, it also produces green-line emission at E region altitudes. Bernhardt et al. (2003) used this technique to reveal kilometric structure in sporadic E layers over Arecibo.

Neutral Wind and Diffusion

Presentations at the workshop included references to combining RF heating with airglow imaging as a way to measure the neutral wind and diffusivity in the thermosphere. This method involves observing clouds of metastable $O(^1D)$ atoms over the heater after heating is discontinued. During this time, these atoms drift with the neutral wind and spread under the influence of diffusion, all the time decaying by radiation and collisional quenching. Using airglow imagery of bright, distinct clouds created by ionospheric modification, Bernhardt et al. (2012) estimated the drift velocity, diffusion rate, and quenching rate of the $O(^1D)$ atoms, in effect using ionospheric modification to perform a kind of repeatable chemical-release experiment.

HAARP-Induced Ionization (“Artificial Ionization”)

As noted in Chapter 1, Todd Pedersen and colleagues (Pedersen et al., 2010) recently demonstrated the capability of the High Frequency Active Auroral Research Program’s (HAARP’s) 3.6-MW transmitter to produce significant artificial plasma in the upper atmosphere. In addition to their fundamental interest, it was pointed out that these results could have important practical implications in communication and over-the-horizon radar as they present the possibility of creating long-path propagation channels on demand that would be otherwise unavailable. The artificial “layers” (the structure of these enhanced ionization regions is an area of current study) are also highly turbulent and so could be used to inhibit as well as promote long-path radio-wave propagation, depending on the desired application.

FUTURE OPPORTUNITIES

Summarized below from workshop presentations, and with additional references added for clarity, are what some participants described as the most promising techniques for basic and applied research into the MLT, thermosphere, and ionosphere using ionospheric modification.

Neutral Density

At the workshop, Elizabeth Kendall described NSF-funded research that has shown—using techniques that are at a research stage and not routine measurement by any means—that ionospheric modification experiments coupled with airglow observations can also be used to estimate neutral density. The long radiative lifetime of $O(^1D)$ means that it is controlled by collisional deactivation (quenching). The quenching rate, in turn, varies with the density of the neutral species in the thermosphere, so, in principle, it is possible to estimate density profiles. The technique requires optical triangulation and the ability to discern emissions from different altitudes. Gustavsson et al. (2001) used a tomographic approach to estimate the decay time of $O(^1D)$ as a function of altitude. Kalogerakis et al. (2009) went further, using the methodology to estimate density profiles of atomic oxygen, which they found dominates the quenching rate above about 200 km.

A workshop participant noted that for all of the methodologies under discussion, knowledge of the ionospheric interaction height is essential for accurate data interpretation. Ionospheric density profiles provided by an incoherent scatter radar (ISR) were said to be the most accurate source of this information. Moreover, electron temperature profiles from an ISR, being diagnostic of electron heating and acceleration, were said to provide vital context for interpreting artificial airglow data. Thus, this researcher stated, quantitatively accurate neutral density profiles at HAARP will most likely require a collocated ISR.

Winds and Temperatures

At the workshop, it was noted that several researchers have suggested a technique for studying the background ionosphere and thermosphere via artificial periodic inhomogeneities (APIs) (Belikovich et al., 1975; Fejer et al., 1984; Rietveld et al., 1996; Djuth et al., 1997; Bakhmet'eva and Belikovich, 2007). In this technique, high-power polarized (X- and O-mode) heating is used to induce very weak variations in the ionospheric index of refraction that follow the structure of the heating standing-wave pattern. Horizontally stratified, vertically periodic structure is thus induced at altitudes from the D region (starting at about 50 km) through the reflection height. Inhomogeneity is created by a combination of ponderomotive and thermal forcing and by photochemical effects, and possibly additional processes.

Once created, the ionospheric structure is diagnosed using HF sounding at frequencies calculated to match to the probe signal to the pump standing-wave pattern. Probing can be done using the same frequency and polarization as the pumping, in which case matching occurs at all heights. It can also be done with the opposing polarization at a different frequency, in which case matching only occurs over a narrow range of heights. The research results note that the advantage of the latter method is that probing and pumping can occur simultaneously, which is generally necessary in the E and F regions where the inhomogeneity decays rapidly.

The decay of the structuring is measured as a function of altitude and in the E and F regions is generally indicative of the ambipolar diffusion rate. Below that, turbulent mixing and photochemistry dominate. From the decay time constant, the electron density and temperature and the neutral density can be estimated. Research has shown that the measurement is straightforward, requires no true-height inversion, and it works in the valley region between the E and F region density maxima, as well as the

main E and F regions themselves. In the D region, electron number density can be measured, and complex photochemical and dynamical processes can be investigated.

Working at EISCAT (European Incoherent Scatter Scientific Association), Rietveld et al. (1996) also examined the Doppler shift of the API backscatter and tentatively associated it with the vertical neutral wind in the D and lower E regions. They reported small (few m/s), zero-mean winds with signs of gravity wave fluctuations. Many workshop participants agreed that this is a remarkable result that holds the promise of very accurate vertical wind measurements in daytime in over a range of altitudes not readily probed by other means. However, it was also noted that implementing the API technique at HAARP would require HF radar capability, either through the use of a collocated system or through the upgrade of HAARP itself.

Diffusion and Cooling Rates and $E \times B$ Drifts

In discussions at the workshop, it was noted that coherent radar scatter from induced plasma density irregularities provides another diagnostic of background parameters in the MLT and thermosphere. A signature feature of ionospheric-modification experiments is the generation of field-aligned plasma density irregularities (FAIs) (Hysell, 2008, p. 117). As noted in Hysell and Nossa (2009), "The irregularities are generated mainly by thermal parametric instabilities (Grach et al., 1978; Das and Fejer, 1979; Fejer, 1979; Kuo and Lee, 1982; Dysthe et al., 1983; Mjølhus, 1990) and, having entered nonlinear stages of development, by resonance instability (Vas'kov and Gurevich, 1977; Inhester et al., 1981; Grach et al., 1981; Dysthe et al., 1982; Lee and Kuo, 1983; Mjølhus, 1993)" (p. 2711). At the workshop, Herbert Carlson and others stated that these irregularities were interesting in their own right and because they also provide bright, regular targets of opportunity for study by coherent scatter radars. Most research has concentrated on F-region FAIs, although irregularities can be generated in the E region by pump waves with low enough frequency.

An example of coherent radar backscatter from E-region FAIs generated over the HAARP facility was provided by David Hysell and is shown in Figure 2.1. In this experiment, the heating pump power was ramped upward and then downward, allowing the determination of the threshold pump electric field required for initiation of thermal parametric instability. This threshold is a function of a number of parameters, including the inelastic electron cooling rate in the E region (Dysthe et al., 1983; Hysell et al., 2010). Because the altitude of the irregularities (where the heating frequency matches the local upper hybrid frequency) is well known, it is possible with this experiment to determine the electron cooling rate accurately as a function of altitude.

Whereas FAIs are created using O-mode heater emissions, research was reported at the workshop that found that simultaneous X-mode emissions can be used simply to heat the modified region. This facilitates tests of the temperature dependence of ionospheric relaxation processes. In the experiment described above (Miceli et. al.; see Figure 2.1), X-mode heating doubled the O-mode power required to generate FAIs. The doubling in this case can be attributed to enhanced absorption caused by heating the D region to approximately 2000 K. The increase in absorption is due both to the temperature dependence of the electron-neutral collision frequency and to changes in electron density arising from temperature-dependent D-region photochemistry. Both processes can be studied and quantified through ionospheric heating.

Moreover, Hysell pointed out that the diffusion rate of FAIs can be studied by monitoring how the coherent radar echoes decline in intensity after the heater is turned off. The decay timescale depends on the probe radar wavelength but is of the order of 100 ms for very-high-frequency (VHF) radars in the E region and a few seconds in the F region. Remarkably, the decay of the irregularities has been found to follow two power laws—one fast, and one slow (Hysell et al., 1996). The faster rate is consistent with ambipolar diffusion and consequently affords another estimate of the temperature, electron-neutral, and ion-neutral collision frequencies and composition at the ionospheric interaction height.

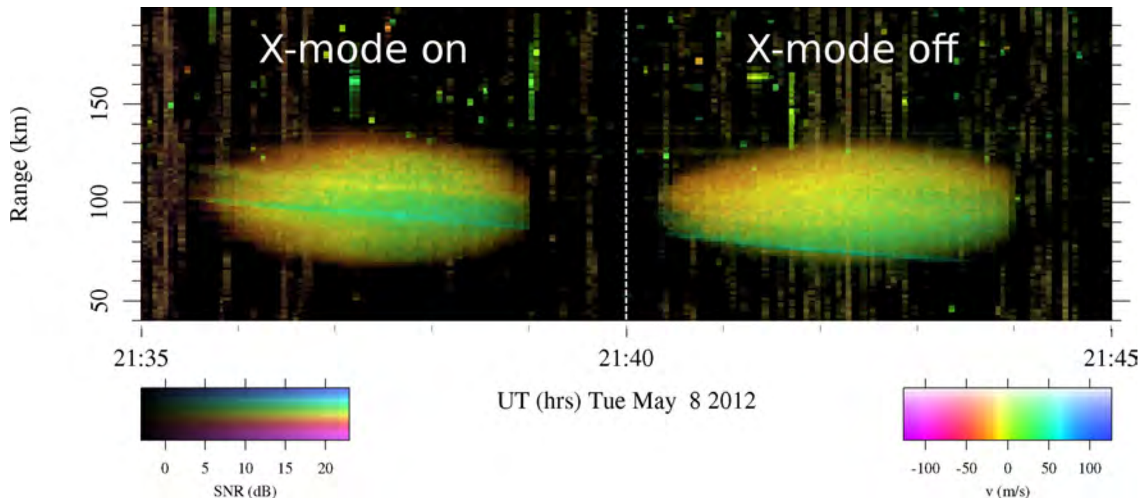

FIGURE 2.1 Range-time intensity plot of coherent echoes from heater-induced field-aligned irregularities over HAARP. The true range to the echoes is the apparent range (shown) plus 370 km. The echoes shown arose from altitudes close to 100 km. Both X- and O-mode emissions were used during the first interval whereas only O-mode emissions were used during the second. SOURCE: Adapted from: R.J. Miceli, D.L. Hysell, J. Munk, M. McCarrick, and J.D. Huba, Reexamining X-mode suppression and fine structure in artificial E region field-aligned plasma density irregularities, *Radio Science* 48:482-490, doi:10.1002/rds.20054, 2013. Available at http://onlinelibrary.wiley.com/doi/10.1002/rds.20054/full. Courtesy of D. Hysell.

In addition to the backscatter power, reported research found that the Doppler shift of the coherent echoes can also be measured during ionospheric modification experiments. Because the echoes have a much longer correlation time than incoherent scatter, the Doppler shifts can be measured far more accurately in a short time. In the F region, the Doppler shifts are indicative of $E \times B$ drifts. Heating experiments, consequently, afford extraordinarily accurate measurements of ionospheric electric fields using SuperDARN-class and similar radars, even where natural ionospheric irregularities are not present.

A workshop participant noted that as with airglow experiments, experiments involving coherent scatter benefit enormously from accurate knowledge of the heating interaction height. This information was said to be most gainfully provided by a collocated ISR.

Ionospheric Conductances

When micropulsations are present, the electric fields inferred from coherent radar scatter are indicative of the electric fields of the Alfvén waves that carry them. Such micropulsations are frequently observed over the Sura heater (Belenov et al., 1997). In what one participant described as a remarkable result, Sinitsin et al. (1999) measured the Doppler shifts of heater-induced FAIs over Sura at three different places along a single magnetic flux tube and found that the three signatures could not be accounted for by a single, shear Alfvén wave. Attributing the signatures to an incident shear wave, a reflected shear wave, and a reflected magnetosonic wave, they were able to infer the Pedersen and Hall conductances at the foot of the flux tube. The authors concluded that this unique experimental capability holds great promise for magnetosphere-ionosphere coupling studies because it has the potential to provide dynamic lower boundary conditions for magnetospheric models in real time.

Ionospheric Instabilities

It was noted repeatedly at the workshop that many important instabilities in the ionosphere can only be created by injecting a large amount of power, such as that available at HAARP. Further, although other instabilities occur naturally, some participants stated that they could be investigated more systematically than is otherwise generally possible using active experiments. An example of the latter kind is the Farley-Buneman instability, which occurs naturally under conditions of strong auroral forcing and creates waves that heat the electrons and modify the ionospheric conductivity. This instability is very sensitive to diffusion and collision rates and their temperature dependencies. Thus, some participants thought it could be possible to modify or even shut off the instability by increasing the E-region temperature with a heater like HAARP.

Another important heater-induced phenomenon is Langmuir turbulence, which has been investigated at Arecibo and EISCAT, where ISRs are available for diagnostics (Isham et al., 2012). As David Hysell explained, Langmuir turbulence enhances the plasma lines seen by ISRs above background levels through a variety of mechanisms, and understanding the effects offers insights into fundamental plasma physics, much in the same way that large colliders offer insights into fundamental particle physics. Langmuir turbulence also appears to generate suprathermal electrons, which cause much of the airglow seen during heating experiments (Djuth et al., 1999).

Making Waves

As noted at the workshop by Mike Taylor and others, the location of HAARP at a subauroral latitude is very interesting for studying the plasmasphere boundary layer and processes that lead to electromagnetic ion-cyclotron waves. At its location, they noted that HAARP can launch waves into this region and do stimulated experiments in radiation modification. It can also be used in studies involving highly elevated electron temperature, excited neutron gas, and the effects they produce, all of which would contribute to the understanding of the mechanisms that generate space weather in subauroral geospace.

Some participants claim that heaters could also potentially produce propagating responses in the ionosphere-thermosphere system, which could then be used to test sophisticated models of the ionosphere. Three-dimensional models have been used, for example, to describe how a localized disturbance at Arecibo would propagate in terms of ion acoustic waves, thermal pulse, density pulse, and so forth, all the way to the conjugate hemisphere, that could be detected by various instruments, especially ISR, at the conjugate point.

It was noted that many questions remain about the day-to-day variations in the ionosphere-thermosphere system and that there has been an increasing appreciation of the importance of "forcing from below," thought to account for perhaps 20 to 30 percent of variability.[2] Discussions among participants pointed to the use of heaters at other latitudes and HAARP to help understand how the complex system responds to such energy inputs. It was suggested that injecting energy into the ionosphere might also clarify the degree to which the ionosphere is involved in substorms and magnetospheric processes; for example, whether there are instabilities or other phenomena in the ionosphere that limit the electric fields or currents that can be carried in the magnetosphere-ionosphere system.

[2] The importance of forcing from below was emphasized by the Panel on Atmosphere-Ionosphere-Magnetosphere Interactions, whose report to the decadal survey committee comprises Chapter 8 of the 2013 report *Solar and Space Physics: A Science for a Technological Society* (NRC, 2013).

Testing Models and Sensor Networks

Participants at the workshop considered how HF modification experiments could be used to provide quantitative parameter assessments for ionosphere-thermosphere models. One participant noted that measuring the response to a local heat input can validate the overall model behavior. Another participant observed that comprehensive study of the global coupled atmosphere will require distributed sensor networks (NRC, 2013), and it was asserted that HAARP could be used as a testbed to provide controlled perturbations for ground-based instrument development.

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3

Magnetospheric Physics

RECENT WORK AND NOTABLE RESULTS

Most recent heater-based studies of magnetospheric processes and ionosphere-thermosphere-magnetosphere (ITM) system couplings use the "virtual antenna" concept, which allows generation and injection of ULF/ELF/VLF (ultralow-frequency/extremely low-frequency/very-low-frequency) waves into the various ionospheric and magnetospheric resonators and waveguides and into the radiation belts. Presentations by Dennis Papadopoulos, Herbert Carlson, Meers Oppenheim, Paul Bernhardt, and others at the workshop highlighted recent and ongoing investigations to show how active ionospheric heating cause-and-effect experiments help resolve critical geospace problems and test predictive space weather forecasting models.

Triggered Emissions

Experiments have shown that the interaction of ELF/VLF waves with energetic electrons in the magnetosphere can enhance or suppress the original waves, generate waves with different or new frequencies, and enhance precipitation of energetic particles trapped in the radiation belts. One unexpected example was the observation of coherent electromagnetic emissions known as chorus emissions. Typically a series of strongly nonlinear rising tones, chorus emissions are generated near the magnetic equator by the interaction of energetic electrons trapped in the radiation belts with self-generated or external ELF/VLF signals. It was stated at the workshop that the underlying physics is both critical to understanding the radiation belts and a serious challenge to the textbook understanding of nonlinear plasma physics.

According to one participant, early studies of the interaction of ground-generated VLF signals with radiation-belt electrons gave a major boost to understanding of triggered emissions (Helliwell, 1988) but were hampered by the limited frequency range (3-6 kHz) of the ground VLF transmitter. Utilizing the High Frequency Active Auroral Research Program (HAARP) as a virtual antenna allowed injection of VLF waves covering a very broad frequency range (0.5-5 kHz) and generated what was described as very interesting preliminary results (Golkowski et al., 2008, 2010). However, the limited number of experiments and the lack of satellite diagnostics did not allow a comprehensive resolution of the issues.

Figure 3.1(a) shows the experimental configuration used in the work by Golkowski et al. (2010). Emissions triggered by ELF/VLF waves injected by HAARP are measured either on the ocean at the conjugate point (one-hop signals) or back at Chistochina, Alaska, 37 km northeast of HAARP (two-hop signals). Figure 3.1(b) shows a spectrogram of injected signals and two-hop echoes received in Chistochina 7 seconds (the round-trip transit time) after the initial pulse. Single-frequency signals between 1 and 3 kHz and frequency sweeps from 0.5 to 3.5 kHz were injected. Echoes were produced only for frequencies between 2.0 and 2.8 kHz, indicative of resonance with anisotropic electrons with energy of 5 to 10 keV.

(a)

(b)

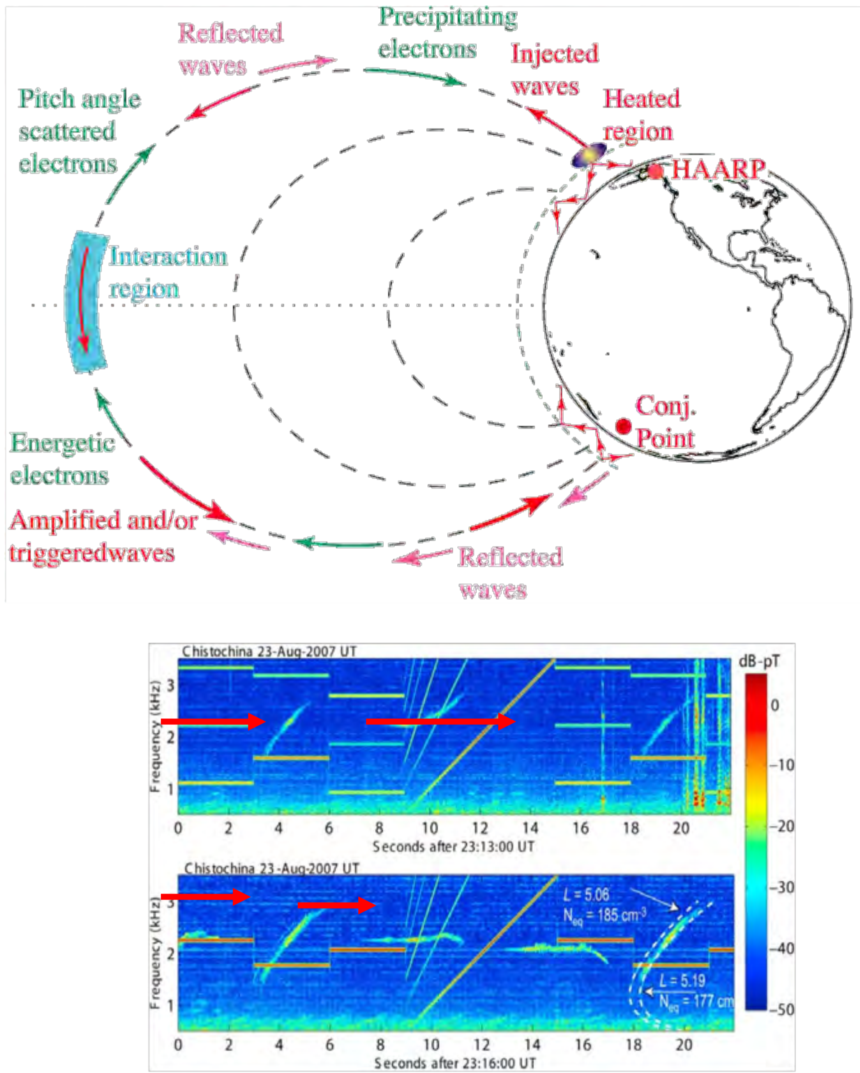


FIGURE 3.1 (a) Schematic of a triggered-wave experiment. Extremely low-frequency/very-low-frequency waves injected into the radiation belts are amplified by interacting with energetic electrons. (b) Two-hop triggered emissions received in Chistochina, Alaska, after reflection at the conjugate point in the South Pacific, connected by red arrows to the signal injected at HAARP. SOURCE: (a) T. Tether, et al., "Future Directions for HAARP," Committee Report, University of Maryland, College Park, Md., May 2001. Available at http://spp.astro.umd.edu/SpaceWebProj/Tether_Panel.ppt.Courtesy of K. Papadopoulos, University of Maryland. (b) M. Golkowski, U.S. Inan, M.B. Cohen, and A.R. Gibby, Amplitude and phase of non-linear magnetospheric wave growth excited by the HAARP HF heater, *Journal of Geophysical Research* 115:A00F04, 2010. Available at http://onlinelibrary.wiley.com/doi/10.1029/2009JA014610/abstract. Courtesy of the Journal of Geophysical Research/John Wiley and Sons.

Guides, Resonators and Magnetosphere-Ionosphere Coupling

In the magnetosphere and ionosphere, ULF/ELF waves are guided by various structures. In addition to the well-known Earth-ionosphere waveguide and the associated Schumann resonances, there can be ionospheric ducts that guide magnetosonic (MS) waves, ionospheric Alfvén resonators (IAR) operating between the D/E region of the ionosphere and the inner plasmasphere at a few thousand

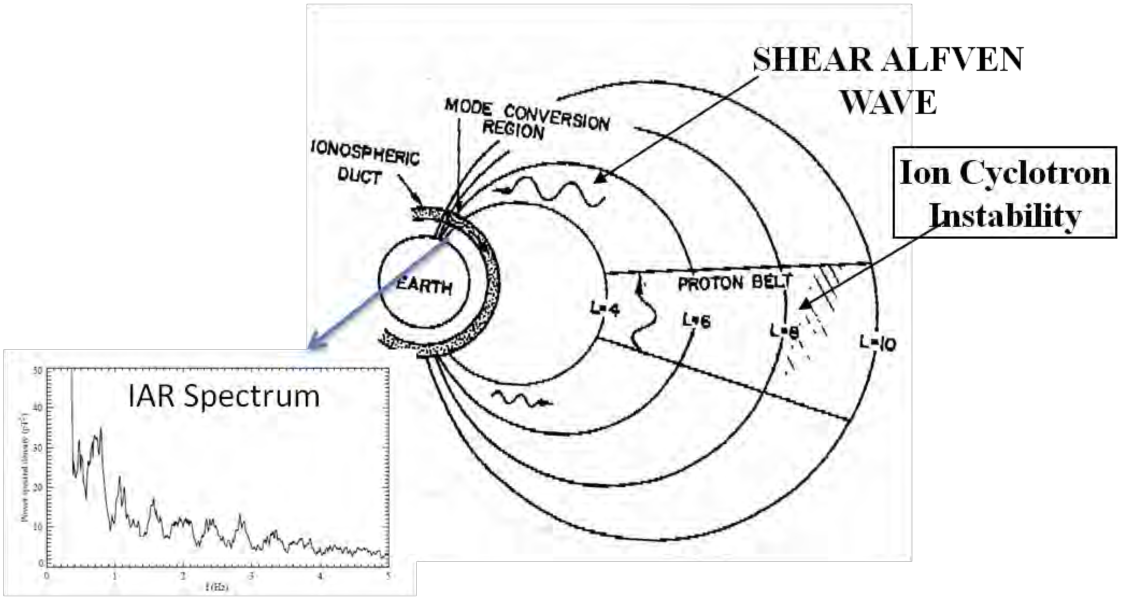


FIGURE 3.2 Example of energy flow starting as shear Alfvén wave, filtered through the ionospheric Alfvén resonator (IAR) and propagating laterally as magnetosonic in the duct. The IAR resonant spectrum on the ground is shown in the inset. SOURCE: Courtesy of K. Papadopoulos, University of Maryland.

kilometers, and magnetospheric resonators for Alfvén and compressional waves. These structures control the coupling of disturbances generated in the high-latitude magnetosphere to the middle- and low-latitude ionosphere. These structures control the propagation and coupling of disturbances generated in the high-latitude magnetosphere to the middle- and low-latitude ionosphere.

Figure 3.2 shows a natural process that couples the magnetosphere to the middle- and low-latitude ionosphere (Lysak, 1999, 2004; Lysak and Song, 2001). Shear Alfvén (SA) waves in the Pc1 frequency range (0.1-5 Hz) generated by ion cyclotron instabilities excite resonant frequencies in the IAR. Mode conversion from SA to MS allows lateral propagation of the energy though the ionospheric duct towards middle and low latitudes. Developing predictive models of such magnetosphere-ionosphere (MI) coupling processes requires quantitative characterization of the three elements involved: the IAR, the ionospheric duct, and the SA/MS coupling. Dennis Papadopoulos informed workshop participants of three examples of recent work at HAARP and EISCAT (European Incoherent Scatter Scientific Association) that show their potential for illuminating these issues:

- Figure 3.3 shows an experiment in which the EISCAT heater injected ULF waves at 3 Hz, and their effect was measured aboard the Fast Auroral Snapshot Explorer spacecraft at altitude 2,550 km (Robinson et al., 2000; Wright et al., 2003). In addition to measuring 3-Hz oscillatory fields in a narrow region that mapped down the magnetic field line to the heated volume, the satellite detected a downward flux of electrons with identical signature to the ELF waves.
- Another goal is determining the *Q* of the IAR. Figure 3.4 shows a recent experiment in which, guided by the presence of naturally excited frequencies at frequencies 0.25 and 0.5 Hz, HAARP excited the 4th harmonic at 1 Hz (Papadopoulos et al., 2011). Notice the narrowness of the spectral line excited by HAARP compared to the naturally excited lines.
- In a third example, Eliasson et al. (2012) used HAARP to explore the transmission through the ionospheric duct. For the first time, MS waves generated by F-region modulation at HAARP were injected in the duct and their signatures were measured at remote sites Washington State (1,300 miles away), Hawaii (2,900 miles), and Guam (4,800 miles).

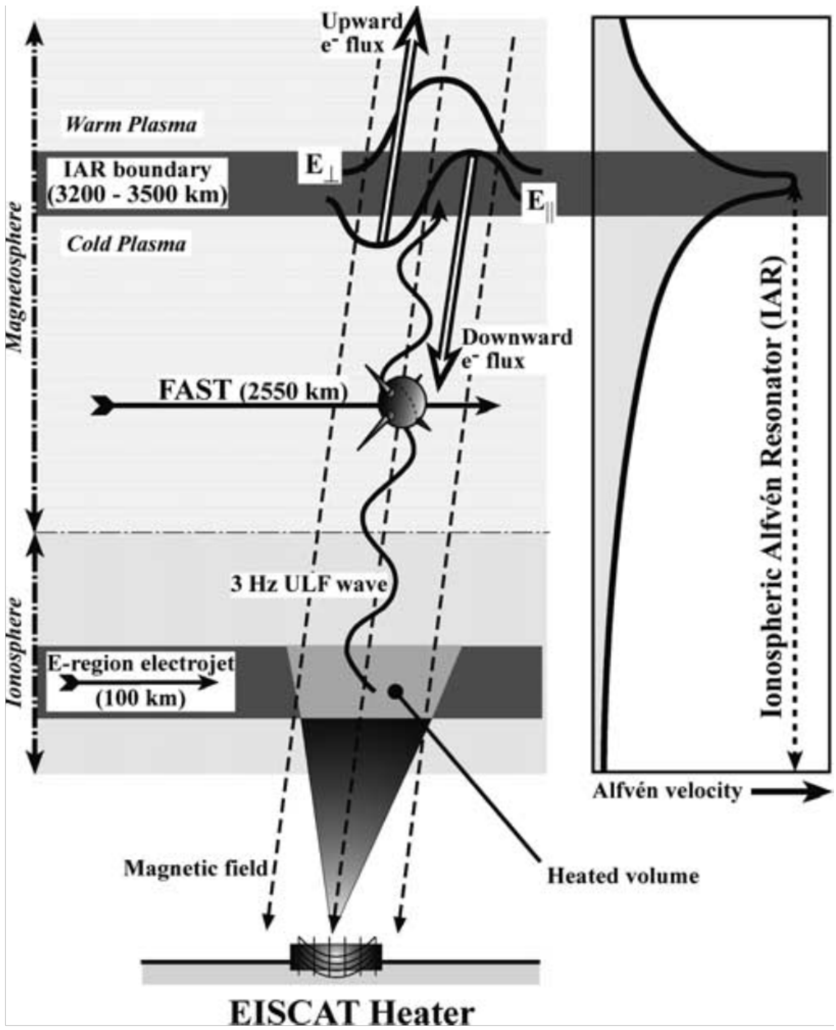


FIGURE 3.3 Schematic of artificial 3-Hz injection in the ionospheric Alfvén resonator (IAR) whose top boundary is at an altitude of about 3,300 km. The wave acquires a significant electric field component parallel to the geomagnetic field above the satellite. NOTE: EISCAT, European Incoherent Scatter Scientific Association; FAST, Fast Auroral Snapshot Explorer; ULF, ultralow frequency. SOURCE: T.R. Robinson, R. Strangeway, D.M. Wright, J.A. Davies, R.B. Horne, T.K. Yeoman, A.J. Stocker, M. Lester, M.T. Rietveld, I.R. Mann, C.W. Carlson, and J.P. McFadden, FAST observations of ULF waves injected into the magnetosphere by means of modulated RF heating of the auroral electrojet, *Geophysical Research Letters* 27:3165-3168, 2000. Available at http://onlinelibrary.wiley.com/ doi/10.1029/2000GL011882/abstract. Courtesy of Geophysical Research Letters./John Wiley and Sons.

FUTURE OPPORTUNITIES

Several participants saw emerging opportunities for discovery research in magnetospheric physics using ionospheric modifications given the following anticipated developments:

1. The availability of heaters at various latitudes to probe different regions of the magnetosphere, corresponding to different L shells (Figure 3.5);
2. The availability of collocated ISRs; and
3. The launch of a number of new satellites anticipated over the next few years.

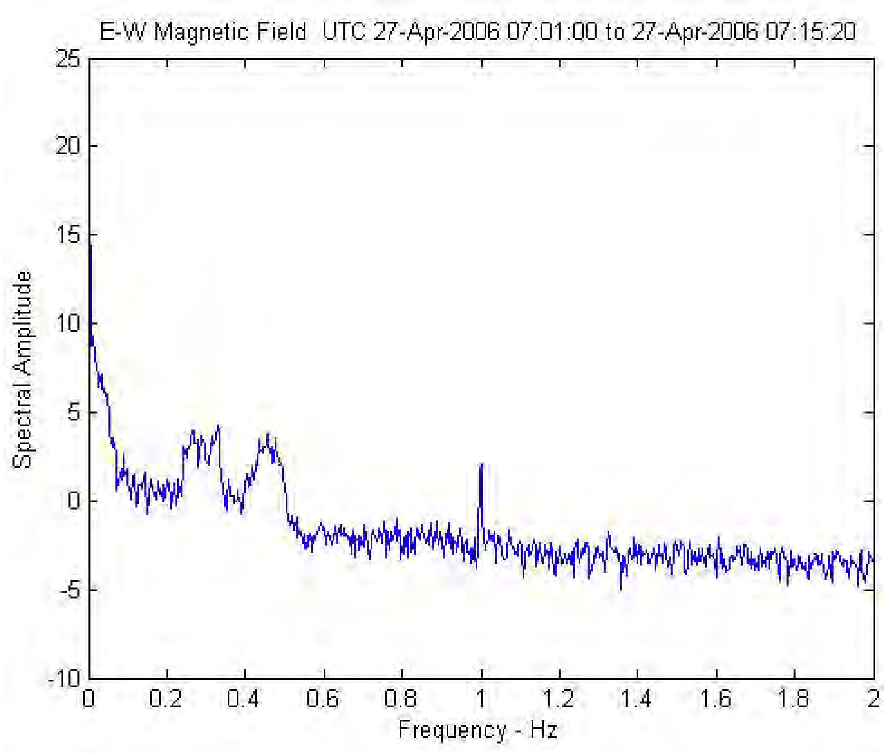


FIGURE 3.4 Natural excitation of the ionospheric Alfvén resonator at 0.25 and 0.5 Hz and artificial excitation by HAARP at 1 Hz. SOURCE: Courtesy of K. Papadopoulos, University of Maryland.

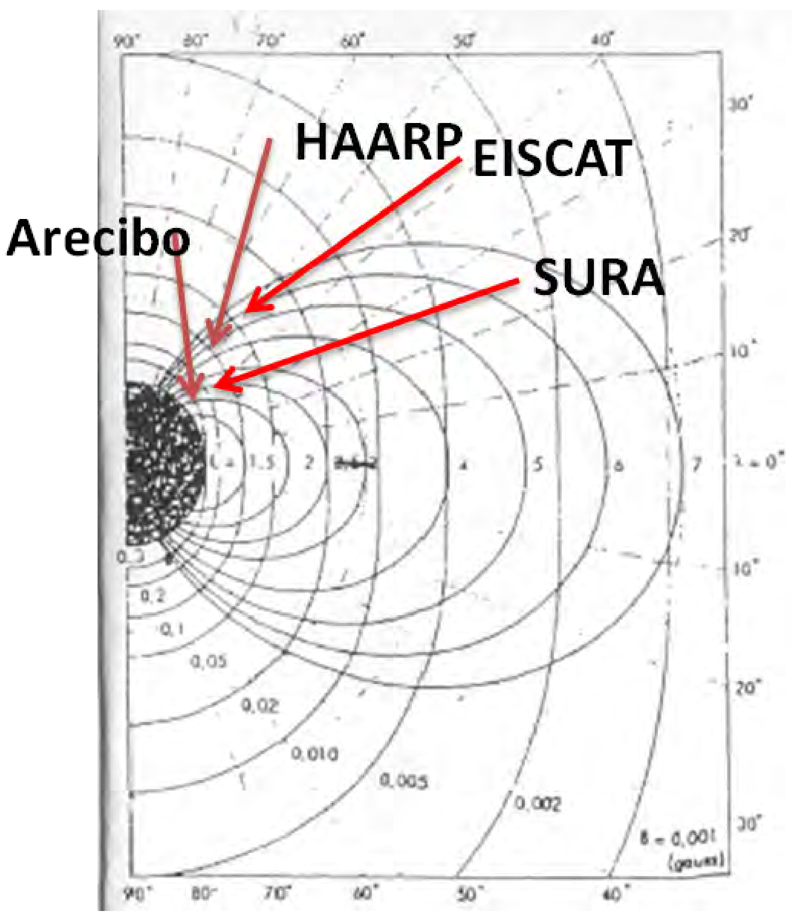


FIGURE 3.5 Ionospheric heaters at various latitudes probe different regions of the magnetosphere corresponding to different L shells: Arecibo (L ≈ 1.4), Sura (L ≈ 2.6), HAARP (L ≈ 4.9), and EISCAT (L ≈ 5.9). NOTE: EISCAT, European Incoherent Scatter Scientific Association; HAARP, High Frequency Active Auroral Research Program. SOURCE: Courtesy of K. Papadopoulos, University of Maryland.

Satellite measurements of the effects generated by ionospheric heating and their propagation toward the magnetosphere and the radiation belts were said to be very important in understanding the physics of the interactions (the example of the occasional HAARP over-flights by the French DEMETER microsatellite were cited). Planned satellite studies of the radiation belts over the next few years will provide numerous opportunities for measuring HAARP-induced phenomena. Key missions include the NASA Van Allen Probes, Canada's e-POP, successfully launched in September 2013, Japan's ERG, to be launched in 2015, and the Air Force DSX, to be launched in 2015. As discussed below, the Russian Space Agency Resonance mission, to be launched in 2014, could be particularly informative.

Solar Wind-Magnetosphere-Ionosphere Coupling; Saturation of the Polar Cap Potential

The cross-polar-cap (or transpolar) potential (CPCP), the difference between the maximum and minimum of the electrostatic potential in the high-latitude ionosphere, has been observed to play a key role in the solar wind-magnetosphere-ionosphere coupling. Because electric fields are mapped onto the ionosphere along the magnetic field lines from the magnetopause and magnetotail, CPCP is an important indicator of the chain of events coupling the solar wind to the ionosphere.

Dennis Papadopoulos sees the ionospheric control of the solar wind-magnetosphere-ionosphere system behavior as a critical outstanding issue in magnetospheric physics. In his view, high-frequency (HF) ionospheric heating experiments at high latitudes, combined with incoherent and coherent radar measurements of the ionospheric dynamics and with multi-satellite observations of the global magnetosphere configuration during both quiet and extreme solar-wind driving conditions, provide unique opportunities to illuminate this process.

Dynamics of the Radiation Belts

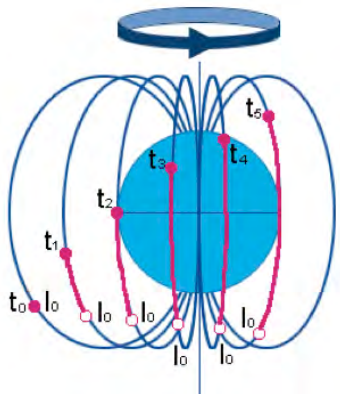
Dennis Papadopoulos led a discussion at the workshop that included consideration of active experiments and the dynamics of Earth's radiation belts. The radiation belts form a natural resonator for many types of waves; as mentioned in Chapter 1, Alfvén and whistler waves can be ducted by gradients of plasma and magnetic field. They oscillate many times along a magnetic field line, being reflected, for example, by the conjugate ionosphere. On the other hand, experiments have shown that these waves interact efficiently with energetic particles (protons and electrons, respectively) via cyclotron resonance, and thus play a critical role in the dynamics of Earth's radiation belts.

Papadopoulos stated that radiation belt studies led to the concept of a magnetospheric cyclotron maser in which energetic charged particles serve as the active gain medium, and the electromagnetic cavity is formed by magnetic flux tubes filled with background (cold) plasma and their ionospheric footprints. Further, he noted that an inhomogeneous distribution of cold plasma plays a twofold role: first, it ensures ducting for the Alfvén and whistler-mode waves along the magnetic field, and second, it makes cyclotron resonant interactions between particles and waves possible, most importantly near the equatorial plane where the magnetic field inhomogeneity is smallest.

Despite the importance and intensive study of magnetospheric-maser interactions, Papadopoulos believes key problems remain unresolved. These include the origin and effects of discrete emissions with fine spectral structure, spatio-temporal dynamics of radiation belts, the role of magnetosphere-ionosphere interactions in the dynamics of magnetospheric cyclotron masers, and similarities and differences between various particular maser systems.

Papadopoulos and other participants discussed how the combination of ionospheric heaters, ISRs, and space-based measurements could provide unique opportunities to resolve these issues. In particular, the scientific potential of a combination consisting of the HAARP HF transmitter, an ISR, and the Russian Resonance satellite mission was cited. The Resonance mission comprises two fully instrumented pairs of micro-satellites in magneto-synchronous orbit (an orbit that rotates with Earth's magnetic field).

(a)



(b)

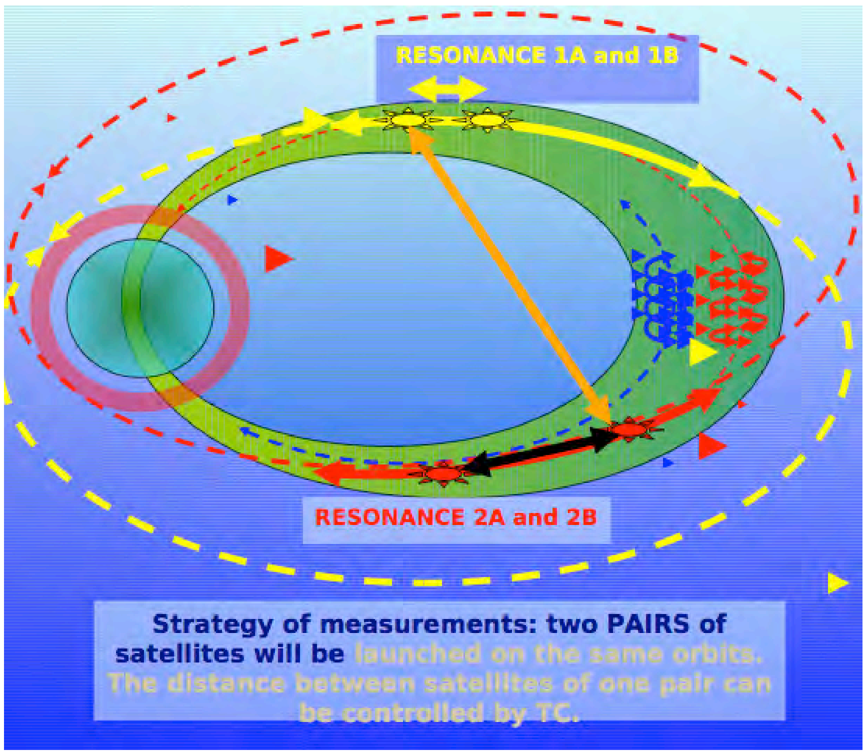


FIGURE 3.6 (a) Magneto-synchronous orbit; the satellite velocity perpendicular to the magnetic field line is equal to the flux tube velocity, allowing the spacecrafts to cover the flux tube over times between 30-45 min. (b) Resonance mission strategy. SOURCE: A. Petrukovich and the Resonance team, “RESONANCE: Project for Studies of Wave-Particle Interactions in the Inner Magnetosphere,” Report of the Resonance Team, HAARP/ RESONANCE Workshop, University of Maryland, College Park, Md., November 8-9, 2011. Available at http://spp.astro.umd.edu/SpaceWebProj/Haarp_Resonance/ap_res2011.pdf. Courtesy of K. Papadopoulos, University of Maryland.

In this orbit, the actual magnetic field line above the HAARP facility can be monitored for periods of 30 minutes or more (Figure 3.6).[1] In addition to providing long integration times, Papadopoulos asserted that this unique magneto-synchronous configuration provides an opportunity to perform “revolutionary” active experiments in which satellite-based instruments provide information about the natural processes

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[1] For further discussion of Resonance and HAARP coordinated observations, see Zelenyi et al. (2004).

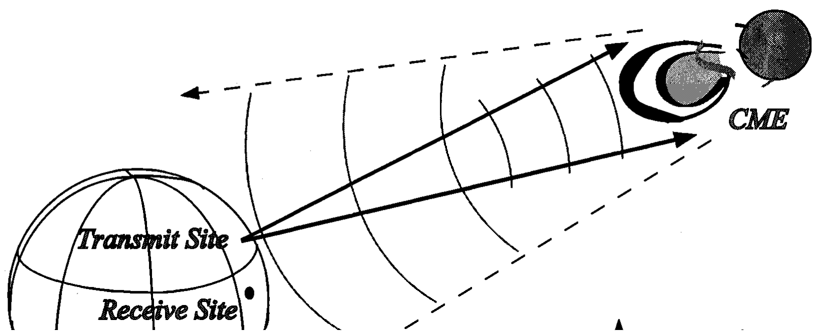

FIGURE 3.7 Schematic of bi-static solar radar for coronal mass ejection (CME) detection. The transmitted signal at a given frequency is shown along with the expected spectral echoes. A CME will produce a more distinct Doppler shift. SOURCE: P. Rodriguez, E. Kennedy, and P. Kossey, "High Frequency Radar Astronomy With HAARP," 2003 IEEE Radar Conference, 2003, available at http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA514972.

occurring in the tube, changes that occur as a result of HF interaction, and how these changes vary in response to changes in the amplitude and phase of the influence. Finally, in addition to ULF/ELF/VLF wave injection, Papadopoulos noted that HF heating allows for controlled modification of the reflection coefficient at F-region heights.

Solar Radar

As background to the discussion of solar radar, Paul Bernhardt noted that studies of the solar corona with HF radars were performed between 1963 and 1969 using a special radar facility in El Campo, Texas, which operated as both a transmitting and a receiving array at 38.25 MHz (Rodriquez, 2000). The results from these experiments "suggested a radar cross section for the Sun's corona of approximately the same size as the optical disk, with occasional expansion by an order of magnitude or more" (Rodriquez, 2000, p. 155). More recently, the Sura heater in Russia was used as transmitter and the UTR-2 facility in the Ukraine as receiver in experiments designed to be close equivalents to an operational solar radar (Rodriquez, 1998).

Coronal mass ejections (CMEs) play an important role in geomagnetic disturbances.[2] Workshop discussions included the potential for solar radars to detect Earthward-moving CMEs, providing several days of advance warning of possible geomagnetic storms. In addition, it was noted that wave scattering in the solar corona might provide information on coronal densities and irregularities. Bernhardt noted that detection of CMEs from Earth using optical techniques is not possible because the geo-effective CMEs are not visible when looking directly at the Sun's photosphere. HF radar scatter from CMEs has been attempted with minimal success using HAARP transmitting at HF and the Jicamarca radar at VHF frequencies, respectively. Bernhardt believes the new Arecibo HF facility in Puerto Rico is especially suited to attempt radar measurements of the Sun and Moon because of its relatively low latitude.

Bernhardt further stated that the potential of HF heaters as bi-static radars for CME monitoring could be tested when the Earth-Sun geometry permits bi-static reception (Figure 3.7) by using the HAARP heater at its maximum frequency as the transmitter and the Arecibo dish as a receiving antenna. The HAARP/Arecibo combination has a 10-dB advantage over El Campo and 14-dB advantage over the Sura/UTR-2 combination. He noted that this configuration could be used for routine detection and

[2] NOAA's Space Weather Prediction Center maintains a website with links to various primers on space weather at http://www.swpc.noaa.gov/Education/index.html.

velocity of average CMEs, velocities of large CMEs at up to 20 solar radii, and polarimetric measurements of magnetic fields in the solar corona and measurements of coronal turbulence using Doppler spectra.

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4

Some Applications of High-Power High-Frequency Facilities

The High Frequency Active Auroral Research Program (HAARP) transmitter is primarily used for basic research into the interactions of high-power radio waves with the high-latitude ionosphere. As noted by many workshop participants, these interactions produce a wide range of effects that may be applied in practical applications. At the workshop, discussions focused on (1) improvement of the space environment, (2) establishment of reliable communications channels, (3) testing of radio propagation systems, (4) simulations of natural disturbances in the ionosphere for mitigation testing, and (5) testing of concepts for high-payoff strategies for removal of space debris.

Table 4.1 aggregates the practical applications of high-frequency (HF), high-power ionospheric heaters such as HAARP that were highlighted by one or more participants at the workshop, especially in a closing wrap-up session.

ENHANCED PRECIPITATION FROM THE RADIATION BELTS

Earth's radiation belts contain high-energy electrons and ions that can damage the electronics of satellites in low Earth orbit. The energetic electrons, spiraling around Earth's magnetic field lines, bounce between the hemispheres at mirror points. If the mirror altitude is below 100 km, the high-energy particles collide with the background neutral atmosphere and lose their energy in the form of optical emissions and enhanced ionization. This process, called precipitation, depletes the energetic population for the electrons that have orbital "pitch angles" that are nearly parallel to the magnetic field lines at their equatorial midpoints.

Using HAARP, researchers can launch ULF/ELF/VLF (ultralow-frequency/extremely low-frequency/very-low-frequency) waves into the magnetosphere to explore their effect on trapped high-energy electrons and protons. Some participants thought that data from these experiments would be important for the design of radiation belt remediation (RBR) systems that could be needed to protect commercial and military satellites if, for example, the radiation belts were "pumped" as a result of an accidental or deliberate high altitude nuclear explosion, or from a Carrington-type space weather event.[1]

IMPROVED TRANSMISSION THROUGH THE IONOSPHERE

At several points in the workshop, participants considered the potential role of heaters in general and HAARP in particular for experiments that would yield information that could be used to improve satellite communication. The plasma irregularities in the ionosphere have long been known to seriously degrade communications and navigation signals from satellites. These ionospheric structures distort and corrugate the phase fronts of very-high-frequency (VHF), ultrahigh-frequency (UHF), and L-band radio waves that propagate through them. A smooth phase front to a ground receiver produces a uniform amplitude pattern at the antenna and minimal signal distortion, but a corrugated wave becomes diffracted by mixing of individual wave components to produce a phase front with large amplitude and phase fluctuations. When this signal reaches a ground antenna, the navigation or communications information can be buried in the noise.

[1] For a description of this event, see NASA (2008) and also NRC (2008).

TABLE 4.1 Practical Uses of High-Power, High-Frequency (HF) Facilities Noted by Individuals at the Workshop

Physical Quantity	HAARP/Arecibo HF Application	Potential Influence	Science
Radiation belt particles	Studies of induced loss with ULF/ELF/VLF wave injection in the radiation belts	Reduced satellite damage	Wave-particle interactions
Field aligned irregularities	Wide scale size generation	Enhanced radio scintillations	Instability and ionization
		Test timing/location algorithms	
		HF radar spread doppler clutter	Propagation and mitigation
Artificial ionization	Local enhanced density production	Artificial radio mirror	Electron acceleration
Artificial aurora	Multiple optical wavelength generation	Space-based optical sensor testing	Electron acceleration and neutral excitation
Stimulated electromagnetic emissions	Electromagnetic noise source	Adjacent channel communications interference	Electrostatic wave diagnostic
HF radar echoes	Radar echoes from sun and meteors	Solar flare/coronal mass ejection detection Asteroid studies	Plasmasphere mapping
Enhanced neutral density	Artificial increase of neutral drag?	Satellite debris deorbit	Ion outflow and neutral drag

NOTE: ULF/ELF/VLF, ultralow-frequency/extremely low-frequency/very-low-frequency.

Research has shown that receiver algorithms that have been designed to work in a high-noise environment can be tested by transmissions of satellite signals through regions of the ionosphere disturbed by the HAARP HF transmissions. At other HF facilities, such as EISCAT (European Incoherent Scatter Scientific Association), Sura, and Arecibo, previous tests of ionospheric effects on UHF (250-MHz) radio signals from satellites have produced amplitude scintillations of 2 dB or less.

Recent observations at HAARP have shown three levels of UHF scintillations from the TACSat4 satellite radiating at 253 MHz.[2] The typical natural level of radio scintillation is 1 dB or less. When the HAARP transmitter is turned on to create field-aligned irregularities but not artificial ionization, the radio scintillation level goes up to about 2 dB. When artificial ionization clouds are made by HAARP, the amplitude fluctuations go up to 15 dB or more. Such strong scintillation levels are only seen naturally when there is a large auroral disturbance in the ionosphere. Real-world testing of satellite communications and navigation (i.e., Global Positioning System) receivers usually requires waiting for natural disturbances to be coordinated with the positions of in orbit. A workshop participant stated that by using HAARP, natural-looking plasma disturbances can be produced at the time that equipment is to be tested for radio scintillation mitigation.

IMPROVED REFLECTION FROM THE IONOSPHERE

HF communications and HF radar systems rely on the ionosphere to refract or scatter ground transmissions back to the ground. The distance between HF ground-to-ground points depends on the altitude of the ionosphere and on the electron density at the peak of the ionosphere layer: The altitude determines the maximum ground range between the HF transmitter and HF receiver, while the density determines the maximum frequency that can be used. Altitude and density fluctuations in the natural

[2] From Paul Bernhardt, paper in preparation and results to be discussed at the December 2013 meeting of the American Geophysical Union. Dr. Bernhardt described these results to the workshop and reported that they were based on his observations during the March 2013 BRIOCHE campaign.

ionosphere limit the reliability and coverage range of HF systems. Some participants thought that HAARP could produce artificial ionization clouds that might provide reliable HF communications paths.

EXPLORING NONLINEAR TRANSMISSION

It is commonly assumed that an HF system with more effective radiated power will have an increased signal-to-noise ratio at the receiver. However, Paul Bernhardt noted that increasing the transmitter power and antenna gain may cause nonlinearities in the ionosphere that will produce self-modulation, self-absorption, and self-scattering. Thus, HF propagation conditions may become worse for transmissions above a certain power. The effect, called stimulated electromagnetic emission (SEE), which introduces additional noise onto the HF signal, is produced by conversion of the electromagnetic wave into electrostatic waves in the ionosphere. These waves can parametrically decay into low- and high-frequency waves that introduce sidebands on the received signals.

Bernhardt stated that the HAARP transmitter has been used to demonstrate that induced sideband distortions of transmitted HF waves can be found at frequencies as low as 7 Hz and as high as 110 kHz for magnetic stimulated Brillouin scatter, stimulated ion Bernstein decay, lower- and upper-hybrid parametric decay, ion-acoustic and electron plasma wave parametric decay, and other modes. He further noted that for transmissions near the harmonics of the electron cyclotron wave, the sideband generation can be very pronounced. Self-absorption occurs when the nonlinear interactions convert part of the electromagnetic signal into dissipative plasma modes such as electrostatic waves and electron heating and acceleration. Self-scatter is caused by high-power HF waves that produce irregularities and density enhancements that deflect the original signal away from the intended receiver. All of these self-interaction processes, says Bernhardt, are coupled by the nonlinearities in the ionospheric plasma. High-power transmissions are used to investigate the practical signal-intensity limit of high-power signals for communications and radar applications.

DETECTING SOLAR EVENTS

See “Solar Radar” in Chapter 3.

ENHANCING SPACECRAFT DRAG

A major problem with old satellites is that they can become space debris. The atmosphere region above 700 km altitude is tenuous and orbiting material, therefore, has a long residence time. It was stated at the workshop that the HAARP facility has been known to produce ion outflow that drags oxygen atoms to an altitude of 800 km. Controlled experiments of this nature—induced ion/neutral species outflow—can improve quantitative modeling of chemical/collisional cross-sections and improve the ability to model processes that can perturb neutral densities or enhance satellite drag. Dennis Papadopoulos believes that HAARP operations, in conjunction with the Canadian CASSIOPE satellite and the Russian Resonance mission, could provide experimental observations of this and other HAARP induced processes. While actual enhancement of satellite drag is at this point only speculation, he and participants, including Elizabeth Kendall, thought the potentially high payoff merited further investigation.

REFERENCES

NASA. 2008, A Super Solar Flare, Science@NASA Headline News, available at http://science1.nasa.gov/science-news/science-at-nasa/2008/06may_carringtonflare/.

NRC (National Research Council). 2008. *Severe Space Weather Events—Understanding Societal and Economic Impacts: A Workshop Report*. The National Academies Press, Washington, D.C.

5

HAARP Diagnostic Instrumentation

The High Frequency Active Auroral Research Program (HAARP) high-power, high-frequency (HF) transmitter gives the means to perform active ionospheric experiments by adding energy to the ionospheric medium using ground-based radio transmissions, also known as radiowave pumping. Radiowave pumping may be applied to experiments that make use of the ionosphere as a plasma laboratory in space and to investigate natural atmospheric processes and parameters via the perturbation of the natural atmospheric state and observation of the results. In both cases, detailed measurements of the results of the pumping or perturbation are required in order to understand the results.

HAARP hosts a set of diagnostic instruments, some owned by HAARP, some owned by HAARP with an associated external principal investigator (PI), and some owned by external institutions and supported by HAARP. Data from all of these instruments are freely available to all researchers. Additional instruments are owned by external PIs and brought to HAARP on a campaign basis. Data from these instruments may or may not be shared with other experimenters. Workshop discussions pertaining to current and potential future instrumentation at HAARP, or of use to experiments at HAARP, are summarized below.

INSTRUMENTATION AT HAARP

Radio Instruments at HAARP

- *Global Positioning System (GPS) scintillation.* There are two GPS scintillation receivers at the HAARP site capable of measuring both phase and amplitude scintillation. Data from one of these receivers is displayed on the HAARP website in addition to relative total electron content (TEC) plus scintillations. Data from both are available to HAARP researchers.[1]
- *GPS total electron content*. To obtain TEC, an Ashtech GPS receiver is used to measure the differential delay between the L-band signals transmitted by each GPS satellite. For each satellite in view, the line-of-sight TEC is computed from this delay measurement and converted to a slab-equivalent vertical TEC assuming uniform horizontal stratification.
- *All-sky riometer*. The all-sky riometer consists of a low-noise receiver connected to a 2 by 2 array of 5-element Yagi antennas operating at 30 MHz. It measures ionospheric absorption by comparing the total power of cosmic radio noise sources in a 30 kHz bandwidth and to average quiet-day data. It has been operating continuously since 1995.
- *Imaging riometer*. The imaging riometer is an 8 by 8 array. It currently suffers from a number of technical problems.
- *ELF/VLF (extremely low-/very-low-frequency) receiver.* This receiver is installed on site, approximately 1 mile from the HAARP transmitter array. It suffers from interference when the HAARP HF transmitters are on, but it can be used to monitor the ELF/VLF background when the HAARP HF transmitters are off.

[1] HAARP website, available at http://www.haarp.alaska.edu/, accessed September 4, 2013.

- *Spectrum monitor.* This instrument measures HF and very-high-frequency (VHF) signals in the background electromagnetic environment. It can be used as a diagnostic of ambient radio propagation. Data have been collected continuously since 1993 and are available on the HAARP website.[2]

Radar Instruments at HAARP

- *Ionosonde.* The HAARP ionosonde is a Digisonde DPS-4D. An ionogram may be completed within 10 seconds. Ionogram and ionospheric drift measurements have been recorded since 1999.
- *30-MHz and 50-MHz coherent radars.* During past campaigns at HAARP, 30- and 50-MHz radars were fielded by the Air Force Research Laboratory. The status of these instruments is unknown.
- *139-MHz (VHF) radar.* This radar operated during 2001 and 2003. Further operation would require an investment in new electronics and software. The radar, when operating, is capable of observing scattering from HF-enhanced Langmuir waves and possibly also ion-acoustic waves. Three receiver channels would enable the simultaneous measurement of ion-acoustic and up and downshifted Langmuir waves.
- *450-MHz (ultrahigh frequency, UHF) radar.* This radar, called the Modular UHF Ionospheric Radar (MUIR), is a phased array consisting of 512 transmit-receive modules each with 500-W peak pulse power. Currently only about half the modules are operational. MUIR can observe scattering from HF-enhanced ion-acoustic and Langmuir waves. The radar could be repaired and an upgraded timing system could be installed to allow synchronization with the HAARP HF transmitter, and two additional receiver channels could be installed to enable the simultaneous observations of ion-acoustic and up- and down-shifted Langmuir waves.

Optical Instruments at HAARP

- *All-sky imagers.* There are two all-sky imagers at the HAARP site, one older and one newer. The older imager is used to collect very-high-quality data during dark sky periods only. The newer imager can make measurements without regard to the position of the Moon, but produces lower-quality images.
- *Telescopic imagers.* This system consists of telescopes with 3- and 19-degree fields-of-view and cooled charge-coupled device imagers. Both are mounted on a computer-controlled mount with 6-position filter wheels and installed in a 14-foot optical dome. The imagers may be operated remotely.
- *THEMIS imager.* This imager is part of an array of ground-based all-sky imagers that support the NASA THEMIS mission.

Magnetometers at HAARP

- *Fluxgate magnetometer.* This instrument is part of the Geophysical Institute Magnetometer Array (GIMA), extending north-south across Alaska, and has been operating continuously since 1998.
- *Induction magnetometer.* This instrument records 3-axis magnetic field perturbations at a 10-Hz sample rate. Data are recorded continuously and displayed as spectrograms on the HAARP website.[3]

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[2] HAARP website, available at http://www.haarp.alaska.edu/, accessed September 4, 2013.
[3] HAARP website, available at http://www.haarp.alaska.edu/, accessed September 4, 2013.

CURRENT USER-PROVIDED INSTRUMENTS

During recent HAARP experimental campaigns, several instruments were fielded by external HAARP experimenters. These include the following:

- *ELF and VLF receivers.* ELF and VLF instruments have been fielded by the University of Florida.
- *HF radio receivers.* HF receivers for measurements of HF-stimulated radio emissions (stimulated electromagnetic emissions or SEE) have been fielded by the Naval Research Laboratory, Virginia Polytechnic and State University, and occasionally by other institutions.
- *Coherent imaging HF radar.* An imaging radar, operating at 30 MHz, operated by Cornell University, is located in Homer, Alaska. The location in Homer allows the observation of plasma irregularities generated in the E region above the HAARP HF transmitter.

RELEVANT SATELLITE MISSIONS

In situ observations of the HF radio-plasma interaction region can be made by instruments carried on sounding rockets and satellites. The most important microsatellite mission, according to Dennis Papadopoulos, is the Russian Resonance mission, which was described in the Chapter 3 section "Dynamics of the Radiation Belts." The following three other satellites, in particular, are of current interest, according to Papadopoulos:

1. *RAX* (Radio Aurora Explorer) is a CubeSat designed to study ionospheric turbulence. It is capable of receiving bi-static scattering from the five incoherent scatter radars (ISRs; Arecibo, Svalbard, Millstone Hill, Poker Flat, and Resolute Bay). RAX was launched in November 2010, and, after a power system failure, a replacement was launched in October 2011. It was noted by Herbert Carlson that the RAX mission to study ionospheric turbulence is very well aligned with capabilities of HAARP, which, unlike nature, can produce ionospheric turbulence effects on demand for coordinated observations.
2. *e-POP* (Enhanced Polar Outflow Probe) is an instrument package carried by the CASSIOPE (Cascade, Smallsat and Ionospheric Polar Explorer) spacecraft. e-POP includes an HF radio receiver operating from several kilohertz to 18 MHz and an energetic electron spectrometer operating from a few 0.1 eV to 100 eV. According to workshop participants, these instruments are ideally suited to in situ observations during HF experiments. The e-POP suite of instruments on CASSIOPE is designed to measure natural outflow with ion and neutral detectors. In addition, the wave and optical sensors flown on e-POP can detect the direct and indirect effects of HAARP at satellite altitudes. As noted above, the e-POP instruments were successfully launched in September 2013.
3. *Swarm* is an European Space Agency minisatellite constellation mission, successfully launched on November 22, 2013, which carries in situ electron and ion density and temperature probes.[4] It was said by a workshop participant to be ideally suited for comparison to incoherent scatter observations, lending small-scale in situ observations to complement the generally larger-scale beam available from ISRs. The wide spatial spread of a large number of probes in the swarm of satellites increases the probability that a Swarm probe will sample the volume of space perturbed by HAARP.

[4] The European Space Agency website for SWARM is http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/Swarm.

DESIRED INSTRUMENTS

Workshop participants discussed a variety of diagnostics that are currently not available at the HAARP facility. The following additions were offered as suggestions by one or more participants who believe they have the potential to enable users to better realize the full potential of the facility; the list should not be interpreted as representing a consensus or lack thereof among participants.

- *ISR.* According to many participants, the most important capability that has been missing from the HAARP program is an ISR. An ISR could be a much larger version of the MUIR radar mentioned above—large enough not only to detect coherent scattering from enhanced plasma waves, but thermal-level or "incoherent" scattering from ion-acoustic and Langmuir waves. Data from thermal-level waves allows the calculation of electron and ion densities and temperatures, and ion outflows, using the highly accurate statistical mechanical plasma theory of those waves. Workshop participants stated that such measurements would be useful for virtually every application of the HAARP HF transmitter. Arecibo, EISCAT (European Incoherent Scatter Scientific Association), and SPEAR all have ISRs collocated with their high-power HF transmitters.
- *Coherent radar systems.* It was noted by Dave Hysell, Paul Bernhardt, and others that HAARP generally has had a lack of radar diagnostics, including not only an ISR, but also other coherent radars. Several participants asserted that repairs, upgrades, or replacements to the other radars mentioned above, including the 139-, 50-, and 30-MHz radars, would be an important asset to the program.
- *HAARP HF radar.* Other participants pointed out that the HAARP HF transmitter and array could be upgraded to allow operation of all and/or part of the array as a coherent HF radar system, complementing other radars with HF radar capabilities in the 2 to 10 MHz range. Herbert Carlson believes that correlating location and time-evolution of images in HF with those in optical emission would be a major contribution to testing, improving, and validating theory and models of instability processes controlling onset and damping of plasma structures constraining trans-ionospheric radio wave propagation for communications and navigation signals.
- *VIPIR HF radar.* The VIPIR (Versatile Interferometric Pulsed Ionospheric Radar) (Grubb et al., 2008) was inspired by the well-known Dynasonde radar (Pitteway and Wright, 1992). Brett Isham noted that the VIPIR is capable of sounding in modes similar to the current HAARP ionosonde, but with significantly enhanced data quality; it can also operate as a very flexible and configurable coherent HF radar.

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Pitteway, M.L.V., and Wright, J.W. 1992. Toward an optimum receiving array and pulse set for the dynasonde. *Radio Science* 27:481-490, doi=10.1029/92RS00269.

6

Outreach and Connections

Several workshop participants noted that support for the High Frequency Active Auroral Research Program (HAARP) and its user base has historically been from the Department of Defense (DOD), with Navy and Air Force support for a variety of military-related applications such as low-frequency communications and associated research in radio frequency (RF) and fundamental physics. In addition to the diagnostic upgrades discussed above, many participants noted that broadening the user base for HAARP would be necessary to fulfill the facilities' potential for leading-edge research. Suggestions included making explicit connections to the well-defined strategic science plans of the National Science Foundation (NSF) Coupling, Energetic, and Dynamics of Atmospheric Regions (CEDAR) program community as well as to NASA and its programs in mesosphere-ionosphere-thermosphere (M-I-T) research, which are informed by strategic documents that include the National Research Council decadal survey in solar and space physics (NRC, 2013). Several workshop participants noted that this outreach to the CEDAR and NASA communities has not been done in the past; however, they suggested that the strong science possibilities brought to light at the workshop make this a valuable opportunity.

One participant suggested that a significant part of this outreach effort could include showing the difference between a "heater facility" and "the investigation of natural phenomena using artificial drivers." While many of the underlying physical processes to be investigated remain the same, the science motivation has a different audience. Another participant noted that traceability to strategic science questions in the NASA and NSF strategic planning documents becomes important. Thus, the addition of the Poker Flat Incoherent Scatter Radar as a significant diagnostic was seen by some participants as a "game changer," moving HAARP from being a facility to which a scientist brings a sensor to a science facility providing both processes for investigation and diagnostics to provide data. It was noted that creating a HAARP facility that includes both a heater and an incoherent scatter radar allows for the investigation of natural phenomena using artificial drivers in which, for example, the energy is generated as high frequency but delivered to the plasma as electron heating, after which the processes follow natural geophysical paths.

Some workshop participants discussed the challenge of how to integrate support from diverse scientific communities and agencies for a shared facility. The addition of improved diagnostic capabilities at HAARP was described as a key element in developing a facility that would be of high interest to both civilian and defense agencies. To familiarize the non-heater-using science community with the usefulness of active experiments, a participant suggested using a "buddy system" for experiments using HAARP, partnering long-time HAARP users with experienced ionospheric observers. Other outreach suggestions included making an effort to be a presence in non-heater sessions of ionospheric conferences and workshops such as CEDAR. (Heater sessions, while standard at a meeting like CEDAR, typically do not attract interest from the greater space science community.) One participant pointed out that a particular difficulty in integrating support among a broader user community will lie in securing support for HAARP operations, which cannot come from Air Force 6.1 (Basic Research) funds,[1] or from NSF science funds.

[1] "While most agencies break out R&D into the three categories of basic research, applied research, and development, DOD divides its RDT&E (research, development, test, and evaluation) account into seven categories,

The importance of demonstrating to the larger research community that active HAARP experiments can be a useful geophysics research tool was noted both by workshop participants who were regular users of HAARP and other heaters and by those who were unfamiliar with active experiments. In this regard, it was observed by Kristina Lynch that the workshop's Focus Area 1, "HF Contributions to M-I-T Science: MLT and Thermospheric Physics," shows the strongest connection to ionospheric strategic science plans. Particularly of note, according to this and some other participants, are the opportunities involving neutral density studies. Focus Area 2, "HF Contributions to M-I-T Science: Ionospheric Physics," was said to also be of interest; however, Lynch and some participants were concerned that the effects of HAARP on magnetosphere-ionosphere coupling would prove to be of too small a scale for conclusive coupling science results. Nevertheless, some participants thought the use of local controlled experiments in the mesosphere and lower troposphere/thermosphere region to address strategic NASA and NSF questions would be able to provide closure on a number of open questions, as delineated in previous sections.

REFERENCES

Koizumi, K. 2005. "R&D in the FY 2005 Department of Defense Budget." Chapter 6 in *AAAS Report XXX: Research and Development FY 2005.* American Association for the Advancement of Science. Available at http://www.aaas.org/spp/rd/05pch6.htm.

NRC (National Research Council). 2013. *Solar and Space Physics: A Science for a Technological Society*. The National Academies Press, Washington, D.C.

each with a numerical code: Basic Research (6.1), Applied Research (6.2), Advanced Technology Development (6.3), Advanced Component Development and Prototypes (6.4), System Development and Demonstration (6.5), Management Support (6.6), and Operational Systems Development (6.7). . . . The 6.1, 6.2, and 6.3 categories are often grouped together as 'Science and Technology.'" From pp. 1-2 of Koizumi (2005).

7

Costs Associated with HAARP Future Operations or Closure

HAARP OPERATING COSTS

The High Frequency Active Auroral Research Program (HAARP) is a $290 million facility. At the workshop, Robert McCoy informed participants that the Air Force Research Laboratory (AFRL) has been spending a total of $7.5 million per year to run HAARP, a number that includes operations and maintenance (O&M) and research dollars. The O&M alone is estimated to be $3 million and the fuel costs are very dependent on the number of hours the heater is operated. Participants were informed by a HAARP user that the cost of sustaining HAARP is probably between $4 million and $5 million. Even though the Department of Defense (DOD) classifies it as a 6.1 (Basic Research) facility, HAARP is funded by AFRL with 6.2 or 6.3 dollars.[1] Options to lower costs and/or develop a pay-per-use approach to operations were also mentioned. Participants were also informed that the Defense Advanced Research Projects Agency (DARPA) BRIOCHE program currently supports research at $3 million for 18 months and spends $1 million per year on HAARP operational costs.

COST OF MOVING THE POKER FLAT INCOHERENT SCATTER RADAR

The following is taken from individual comments made at the workshop:

- The cost of moving the Poker Flat Incoherent Scatter Radar (PFISR) to Gakona, Alaska, is estimated to be $700,000 to $1 million. This number is based on "ROM costing"—rough order of magnitude—by SRI.
- The National Science Foundation (NSF) has stated that they would help with moving costs provided that a large fraction of the move (greater than 60 percent) is paid for from other sources. DARPA was said to be considering contributing some $250,000 to the cost of the move.
- NSF also stated that they would pay the operating costs for PFISR at HAARP; however, this assumes that the facility is run at high power no more than about 2,000 hours per year. Power at HAARP is generated onsite and is thought to be cheaper than power at Poker Flat.
- The construction of a horizontal structure for a HAARP Advanced Modular Incoherent Scatter Radar (AMISR) at Gakona, Alaska, was costed by Marsh Creek at $200,000.

REMEDIATION

Colonel John Haynes stated that were no remediation costs associated with HAARP under the bill of sale. However, workshop participants also were informed of an environmental impact statement, recently signed-off by the Secretary of the Air Force, that states that at such time that the HAARP program is terminated, all structures are to be removed, gravel pads are to be flattened out, and the entire

[1] As noted in Chapter 6, the code 6.2 refers to Applied Research, and 6.3 to Advanced Technology Development (6.3), from Koizumi (2005).

site is to be covered in dirt and re-grassed with the local vegetation. At the meeting, a cost number of $15 million was mentioned by one official as a good starting estimate for this remediation.

COST OF UPGRADING HAARP TO A HIGH-FREQUENCY RADAR

As noted above, one of the upgrades to HAARP mentioned at the meeting would allow operation as a high-frequency (HF) radar. Todd Pedersen stated that if the receiver array were set up like the new Long Wavelength Array (LWA) near the Very Large Array (VLA) in New Mexico, it would cost about $1 million, which would fit within the threshold for a DOD "Phase II" SBIR (Small Business Innovation Research) award.

POTENTIAL NSF FUNDING OPPORTUNITIES

The following are potential funding opportunities through NSF grants that some participants suggested could be used as possible avenues of support for the continuation of the HAARP program. Questions about what percentage of these grants can be used to support operating costs were not addressed at the workshop.

- The NSF Science and Technology Center (STC) program, now up to $5 million per year, supports integrated science, technology, education, knowledge transfer, and diversity. A workshop participant noted than an STC needs a strong and compelling science focus; for example, biophotonics, nanotechnology, space weather, or networked sensors.[2]
- The Engineering Research Center (ERC) program offers grants as large as $20 million or more and supports centers that promote a "culture in engineering research and education that integrates discovery with technological innovation to advance technology and produce graduates who will be creative U.S. innovators in a globally competitive economy. . . . [The centers are] comprised of a university program and a pre-college program. The university education mission of an ERC is to prepare students for effective practice in industry and to enhance their capacity for creative and innovative leadership throughout their careers. The pre-college education mission rests on long-term partnerships with K-12 institutions to expose teachers to engineering and deliver engineering concepts and experiences to their classrooms to stimulate student interest in engineering careers."[3]
- The Experimental Program to Stimulate Competitive Research (EPSCoR) program office supports infrastructure in EPSCoR jurisdiction states. Alaska is one, and Puerto Rico is another. These are large awards—more than a million dollars per year. EPSCoR also supports projects that are collaborations between two EPSCoR jurisdictions; for example, Alaska and Puerto Rico.

REFERENCE

Koizumi, K. 2005. "R&D in the FY 2005 Department of Defense Budget." Chapter 6 in *AAAS Report XXX: Research and Development FY 2005.* American Association for the Advancement of Science. Available at http://www.aaas.org/spp/rd/05pch6.htm.

[2] See "Science and Technology Centers (STCs): Integrative Partnerships," at the NSF website, http://www.nsf.gov/od/iia/programs/stc/.

[3] National Science Foundation, Engineering Research Centers, available at http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5502.

Appendixes

A

Statement of Task

An ad hoc committee will plan a 3-day public workshop on the role of high-power HF-band transmitters in upper atmospheric research. The topics for discussion at the workshop may include the following:

1. What is the state of the art in active ionospheric and thermospheric research?
2. What are the fundamental research areas in ionospheric science that can be addressed using high-power HF-band transmitters?
3. What are the key diagnostic instruments needed in conjunction with high-power HF-band transmitters to address items 1 and 2?
4. Are there emerging science questions that might benefit from active ionospheric experiments in the subauroral zone?
5. What operating parameters (e.g., power and transmission frequency) are needed to address the questions in items 1-4?
6. Are there ways to combine similar facilities (e.g., EISCAT, Arecibo) to perform global ionospheric science?
7. What research opportunities might arise from the relocation of the AMISR incoherent scatter radar from the Poker Flat Research Facility in Poker Flat, AK, to Gakona, AK, the location of the HAARP facility?

The committee will hold organizing sessions by teleconference to develop the agenda for the workshop and to define the specific topics for invited presentations and discussions. The committee will subsequently select and invite speakers and other participants and moderate the discussions at the event. The committee will prepare a workshop report that will summarize what transpired at the event but will not contain any findings, conclusions or recommendations.

B

Workshop Agenda

MAY 20-22, 2013
NATIONAL ACADEMIES KECK CENTER
WASHINGTON, DC

May 20, 2013

8:00 am Welcome, Plan for the Workshop, and Participant Introductions

Lou Lanzerotti, New Jersey Institute of Technology and Workshop Committee Chair
Art Charo, Space Studies Board

8:30 View From the Sponsors—Department of Defense (Air Force Office of Scientific Research) and National Science Foundation (GEO/AGS)

Kent Miller, Air Force Office of Scientific Research
Rich Behnke, National Science Foundation

Science and HF Active Experiments—Background for Workshop

9:00 Current HF Experiments and Capabilities Related to Workshop Statement of Task

Dennis Papadopoulos, University of Maryland
Dave Hysell, Cornell University
Paul Bernhardt, Naval Research Laboratory

10:00 Questions and Comments

10:45 Magnetosphere-Ionosphere-Thermosphere Science Objectives: Guidance from the Decadal Survey, CEDAR/GEM, and Geo Vision

Josh Semeter, Boston University

11:20 Moderated Discussion: Development of Topics for Extended Discussion in the Four Workshop Focus Areas

Elizabeth Kendall, SRI International

12:30 pm Working Lunch

Focus Area I: HF Contributions to M-I-T Science: MLT and Thermospheric Physics

1:30 Overview of Basic Issues in MLT (mesosphere/lower thermosphere) and Thermospheric Physics *(15-minute presentations)*

Mike Taylor, Utah State University
Tom Slanger, SRI International
Lara Waldrop, University of Illinois
Andrew Nagy, University of Michigan

2:30 Moderated Discussion: The Significance and Relevance of Current and Potential Contributions of HF Research to FA-I (in context of the statement of task)

Dave Hysell, Cornell University

Focus Area II: HF Contributions to M-I-T Science: Ionospheric Physics

3:45 Overview of Basic Issues in Ionospheric Physics *(15-minute presentations)*

Larry Paxton, Johns Hopkins University Applied Physics Laboratory
Meers Oppenheim, Boston University
Joe Huba, Naval Research Laboratory
Rob Pfaff, NASA Goddard Space Flight Center

4:45 Moderated Discussion: The Significance and Relevance of Current and Potential Contributions of HF Research to FA-II (in context of the statement of task)

John Foster, MIT Haystack Observatory

5:45 Adjourn for the Day

6:00 Committee Dinner for Organizers and Invited Guests

May 21, 2013

Focus Area III: HF Contributions to M-I-T Science: Magnetospheric Physics

8:30 am Overview of Basic Issues in Magnetospheric Physics (*15-minute presentations)*

Bob Clauer, Virginia Polytechnic and State University
Chia-Lie Chang, BAE Systems
Lars Dyrud, Johns Hopkins University Applied Physics Laboratory

9:30 Moderated Discussion: The Significance and Relevance of Current and Potential Contributions of HF Research to FA-III (in context of the statement of task)

Dennis Papadopoulos, University of Maryland

Focus Area IV: HF Contributions to Applied and Operational Programs

11:00 Overview of Basic Issues Related to Ionospheric Modification *(15 minute presentation)*

Jade Morton, Miami University (Ohio)
Todd Pedersen, Air Force Research Laboratory
Evgeny Mishin, Air Force Research Laboratory

12:00 pm Working Lunch

1:00 Moderated Discussion: The Significance and Relevance of Current and Potential Contributions of HF Research to FA-IV (in context of the statement of task)

Paul Bernhardt, Naval Research Laboratory

2:10 Additional Topics for Workshop Discussion

- Emerging science questions that could benefit from HF modification experiments
- The role of collocated incoherent scatter radars
- Applications and the impact of HF experiments on space weather, communications, and other areas in the national interest

3:15 Examining the Costs, Benefits, Trades, and Key Issues among the Options Identified in the Workshop

4:00 Wrap-up: Summarize Key Take-Away Items for Further Exploration

4:30 Workshop Adjourns

May 22, 2013

8:30 am Organizing Committee Convenes

- Recap
- Next Steps for Production of Workshop Summary

12:00 pm Adjourn/Lunch

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Workshop Participants

WORKSHOP ORGANIZING COMMITTEE

Louis J. Lanzerotti *Chair*, New Jersey Institute of Technology
Paul A. Bernhardt, Naval Research Laboratory
Herbert C. Carlson, Utah State University
Anthea J. Coster, Massachusetts Institute of Technology
John C. Foster, Massachusetts Institute of Technology
Sixto A. González, Arecibo Observatory/SRI International
David L. Hysell, Cornell University
Brett Isham, Interamerican University, Bayamón, Puerto Rico
Elizabeth A. Kendall, SRI International
Kristina A. Lynch, Dartmouth College
Konstantinos (Dennis) Papadopoulos, University of Maryland

GUESTS

Richard Behnke, National Science Foundation (NSF) GEO/AGS
Chia-Lie Chang, BAE Systems
Bob Clauer, Virginia Polytechnic and State University
Lars Dryud, Johns Hopkins University Applied Physics Laboratory
Lt. Col. Jose Harris, Chief of Space Operations Plans, HQ USAF/A3O-W
Col. John Haynes (ret.), U.S. Air Force, SAF/AQRT
Joe Huba, Naval Research Laboratory, Washington, D.C.
Rob Jacobsen, Marsh Creek, McLean, Virginia
John Luginsland, Air Force Office of Scientific Research (AFOSR)/RTB
Mike McCarrick, Marsh Creek, McLean, Virginia
Robert McCoy, University of Alaska, Fairbanks
Kent L. Miller, AFOSR/RTB
Evgenii Mishin, Air Force Research Laboratory
Jade Morton, Miami University (Ohio)
Andy Nagy, University of Michigan, Ann Arbor
Meers Oppenheim, Boston University
Larry Paxton, Johns Hopkins University Applied Physics Laboratory
Todd Pedersen, Air Force Research Laboratory
Rob Phaff, NASA GSFC
Robert Robinson, NSF GEO/AGS
Anne-Marie Schmoltner, NSF GEO/AGS
Josh Semeter, Boston University
Tom Slanger, SRI International, Palo Alto, California
Mike Taylor, Utah State University
Lara Waldrop, University of Illinois

D

Committee Biographical Information

LOUIS J. LANZEROTTI (NAE), *Chair*, is the Distinguished Research Professor of Physics at New Jersey Institute of Technology (NJIT), has spent four and one-half decades contributing to research that includes studies of space plasmas and geophysics, and engineering problems related to the impact of atmospheric and space processes on terrestrial technologies, and those in space. Prior to joining NJIT in 2003, Dr. Lanzerotti spent more than three decades at Bell Laboratories-Lucent Technologies, Murray Hill, NJ. Dr. Lanzerotti has been principal investigator or co-investigator on a number of NASA Earth observing, interplanetary and planetary missions including IMP, Voyager, Ulysses, Galileo, and Cassini. He is currently a principal investigator for instruments on NASA's Radiation Belt Storm Probes mission in Earth's magnetosphere. Dr. Lanzerotti's research is directed toward understanding Earth's upper atmosphere and space environments has also taken him to the Antarctic and the Arctic. Dr. Lanzerotti was selected as the 2011 William Bowie Medalist of the American Geophysical Union (AGU). He has also received the William Nordberg Medal for applications of space science from the International Committee on Space Research (COSPAR). Dr. Lanzerotti has been elected to the National Academy of Engineering (NAE) and the International Academy of Astronautics (IAA). He is the recipient of the 2012 Basic Science Award of the IAA. He holds a B.S. in engineering physics from the University of Illinois and a M.S. and Ph.D. in physics from Harvard University. Dr. Lanzerotti has had extensive NRC service, most recently serving as chair of the NRC Committee on Electronic Vehicles Controls and Unintended Acceleration. He is currently a member of the Committee on Solar and Space Physics.

PAUL A. BERNHARDT is a senior research physicist in the plasma physics division at the Naval Research Laboratory where he has been conducting research at ionospheric modification facilities since 1985. He has worked at the Arecibo, EISCAT (European Incoherent Scatter Scientific Association), Sura, and High Frequency Active Auroral Research Program (HAARP) heating facilities. Dr. Bernhardt has pioneered the use of chemical releases to study the ionosphere. His ionospheric modification experiments have been monitored with Incoherent Scatter Radar (ISR) systems around the world and with in situ plasma probes provided by NRL's Plasma Physics Division. The Coherent Electromagnetic Radio Tomography (CERTO) and Computerized Ionospheric Tomography Receiver in Space (CITRIS) programs were started at NRL by Dr. Bernhardt to provide global, satellite-based sensors of ionospheric space weather. Dr. Bernhardt has published over 100 papers in ionospheric and space physics. He holds patents for hyper-spectral imaging and radio beacon design. He is a fellow of the APS, the European Physical Society (EPS) and the Institute of Electrical and Electronics Engineers (IEEE). He has been an associate editor of the AGU's Journal of Geophysical Research (JGR) and the Journal of Radio Science as well as a member of the AGU Books Board Editor. He is also a member of the International Union of Radio Science (URSI) where he was chairman of the US Commission on Waves in Plasmas. Dr. Bernhardt received his B.S. degree in electrical engineering from the University of California at Santa Barbara, and his M.S. and Ph.D. in electrical engineering from Stanford University. He previously served on the NRC's U.S. National Committee for the International Union of Radio Science.

HERBERT C. CARLSON is a research professor and scientific lead in the Department of Physics, Center for Atmospheric and Space Sciences, at the Utah State University. His research interests include space and ionospheric physics, ionospheric modification with high power HF radio waves, and radio science. Prior to joining Utah State, he served for 7 years as Chief Scientist of the Air Force Office of Scientific Research within the cadre of the Senior Executive Service and was awarded the Presidential Rank Award for service to the nation. He is an elected foreign member of the Norwegian Academy of Sciences, the Royal Astronomical Society of London, and he is a fellow of the Air Force Research Laboratory and the Phillips Laboratory. His prior federal service also includes service as NSF program manager of aeronomy and atmospheric chemistry, as founding manager of the NSF upper atmospheric facilities program, as chief scientist at the Air Force geophysics laboratory (AFGL), and as deputy director and branch chief ionospheric physics at AFGL. He has also worked at Cornell University, Rice University, Yale University, and University of Texas, Dallas. Dr. Carlson has over 1300 citations to over 150 publications/books and an index of 30. He has served as advisor to 18 successful Ph.D. candidate students in the U.S. and abroad. He has chaired or served on advisory boards for organizations in industry, academia, and the federal government. He received his Ph.D. in space science from Cornell University.

ANTHEA J. COSTER is a principal research scientist at the MIT’s Haystack Observatory in Westford, Massachusetts. Her research interests include physics of the ionosphere, magnetosphere, and thermosphere; space weather and geomagnetic storm time effects; coupling between the lower and upper atmosphere; GPS positioning and measurement accuracy; radio wave propagation effects; and meteor detection and analysis. She is a co-principal investigator on the NSF supported Millstone Hill Geospace facility award and a principal investigator/co-principal investigator on a numerous projects involving the use of GPS to probe the atmosphere, including investigations of the plasmaspheric boundary layer, stratospheric warming, and the ionosphere over the Antarctic. Dr. Coster and her co-workers developed the first real-time ionospheric monitoring system based on GPS in 1991. She has been involved with measuring atmospheric disturbances over short baselines (GPS networks smaller than 100 km) for the U.S. Federal Aviation Administration, and has coordinated meteor research using the ALTAIR dual-frequency radar for NASA. Dr. Coster is the current secretary of the Satellite Division of the Institute of Navigation and the former chair of USNC/URSI commission G. She is currently involved with educational outreach programs that involve scientists in Africa, and teaching in incoherent scatter radar summer schools. She received her Ph.D. in space physics and astronomy from Rice University, and her graduate research involved ionospheric modification experiments at the Arecibo Observatory in Puerto Rico. Dr. Coster previously served on the NRC’s U.S. National Committee for the International Union of Radio Science.

JOHN C. FOSTER is an associate director and ionospheric and space physicist at MIT’s Haystack Observatory. His research interests include the physics of the magnetosphere, ionosphere, and thermosphere, geospace studies and magnetosphere-ionosphere-atmosphere coupling, space weather and storm-time effects, wave-particle interactions, incoherent scatter radar and radiophysics. He has worked with space and ground-based instrumentation and observations through research and management positions at the National Research Council of Canada, Utah State University, and MIT. He served for 25 years as the principal investigator for the MIT Millstone Hill incoherent scatter radar. Dr. Foster has had a 30-year involvement with the NSF CEDAR (Coupling, Energetic, and Dynamics of Atmospheric Regions) research program and community and most recently served as chair of the CEDAR Science Steering Committee. He received his Ph.D. in physics from the University of Maryland College Park. He has been on several NRC committees, including the Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop, the Committee on Solar Terrestrial Research, the Committee on Solar and Space Physics, and he served as a member of the steering committee of the 2001 Decadal Survey of Solar and Space Physics.

SIXTO A. GONZALEZ is director for space and atmospheric sciences at the Arecibo Observatory, part of the Center for Geospace Studies at SRI International. Previously, he served as director of the Arecibo Observatory. His research interests include studies of the Earth's upper atmosphere (specifically, the ionosphere-thermosphere and protonosphere-exosphere coupled systems) using incoherent scatter radars, satellites, and optical instruments together with physics based numerical models. Another major topic of research has been in the general area of incoherent scatter radar theory, for example, exploring ways to improve the experimental techniques in order to improve both the precision and accuracy of the radar observations. Dr. González has served on numerous NASA and NSF panels and committees including 2 terms a vice-chair of COSPAR commission C and one term as chair of the CEDAR science steering committee. He received his Ph.D. in physics from Utah State University.

DAVID L. HYSELL is a professor in the department of earth and atmospheric science at Cornell University. His research is in the area of space plasma physics with a concentration on theory and observations of plasma irregularities in the earth's ionosphere. Dr. Hysell is the principal investigator of the NSF award that supports research at the Jicamarca Radio Observatory near Lima, Peru. He also performs experiments using a network of radars and other instruments with support from NSF, NASA, ONR, AFOSR, and DARPA. He currently serves as the chair of the CEDAR Science Steering Committee, is a member of the U.S. National Committee for URSI, and has just completed service on the Executive Committee for Space Physics and Aeronomy at the AGU. Dr. Hysell currently serves on the Committee on Solar and Space Physics, and recently completed service on the steering committee for the 2013 Decadal Survey for Solar and Space Physics. He is also an ex officio member of the NRC's U.S. National Committee for the International Union of Radio Science.

BRETT ISHAM is a professor in the department of electrical engineering at Interamerican University of Puerto Rico, Bayamon. Dr. Isham has worked at the Swedish Institute for Space Physics in Kiruna, Sweden, the Arecibo Observatory in Puerto Rico, and at the EISCAT Observatories in Tromso, Norway, and Longyearbyen on the island of Spitsbergen in the Arctic Ocean. Dr. Isham's research has focused on the experimental study and remote sensing of microscopic plasma turbulence in the terrestrial ionosphere, primarily using radio and radar methods, and he is one of the discoverers of Langmuir turbulence occurring in the natural aurora. He has also been involved in projects to study tides, waves, and aerosols in the neutral atmosphere and the plasma dynamics of the solar corona. His current interests include plasma turbulence in the ionosphere, the development and application of phase-coherent radio receivers to the study of ionospheric plasma turbulence and radio orbital angular momentum, the development of electromagnetic vector sensor antennas for detection and identification of radio sources, lidar (laser radar) observations of aerosols and ions in the lower and middle atmosphere, and the use of conducting laser-plasma filaments in the neutral atmosphere for communications and remote sensing. Dr. Isham is a member of Phi Beta Kappa, Tau Beta Pi, the American Geophysical Union, and the International Union of Radio Science (URSI). He received his Ph.D. in space physics from Cornell University.

ELIZABETH A. KENDALL is a research physicist at SRI International in Menlo Park California. Her research interests include observations of optical emissions caused by ionospheric modification, auroral and airglow imaging, lightning effects on the upper atmosphere, and education outreach. She is currently a participant in the BRIOCHE program and conducts experiments at the HAARP facility in Gakona Alaska. She has participated in HAARP campaigns for over a decade. Dr. Kendall is the principal investigator for the all-sky imagers at the Sondrestrom Research Facility in Kangerlussuaq Greenland and provides data to the community. She was co-principal investigator on the CESAR (Compact Echelle Spectrograph for Aeronomic Research) instrument, a major research instrument funded by NSF. Dr. Kendall served on the steering committee for the Radio Frequency Ionospheric Interactions workshop for 7 years, first as a student representative and then as a regular member. She has also served on the steering

committee for NSF's ISR Summer Schools for over five years, participating both in organizing the schools and as a lecturer. She received her M.S. and Ph.D. in electrical engineering from Stanford University.

KRISTINA A. LYNCH is an associate professor of physics and astronomy at Dartmouth College. Prior to arriving at Dartmouth, Dr. Lynch was a research assistant professor at the University of New Hampshire. Her research focuses on auroral space plasma physics, ionospheric and mesospheric sounding rocket experiments, instrumentation, and data analysis, and wave-particle interactions in the auroral ionosphere. She has a Ph.D. in space plasma physics from the University of New Hampshire. She most recently completed service on the NRC heliophysics decadal survey's Panel on Atmosphere-Ionosphere-Magnetosphere Interactions, and also served on the Committee on Heliophysics Performance Assessment, the Committee on Solar and Space Physics, and the Committee on Plasma 2010: An Assessment of and Outlook for Plasma and Fusion Science.

KONSTANTINOS (DENNIS) PAPADOPOULOS is professor in the Departments of Physics and Astronomy at the University of Maryland, College Park. He has worked for over 40 years in the areas of basic plasma physics, thermonuclear fusion, space plasma physics and laser solid state plasma interactions. Dr. Papadopoulos has published over 280 papers in refereed journals, presented over 120 invited papers in international meetings, edited two books and is the recipient of six patents. He was selected as principal investigator in several NASA missions, including the Tethered Space Science Missions (TTS-1 and 2), the Global Geospace Science (GGS) Mission and the CRESS Mission and has directed numerous projects under NSF, DOE, and DOD sponsorship. He is a discoverer of spontaneously created magnetic fields in laser-produced plasmas, and his work on ionospheric heating and ELF/VLF generation using HF radio-waves interacting with the ionosphere spurred the construction of the HAARP heating facility in Alaska and to the associated applications in low-frequency communications, underground imaging and Radiation Belt control. His early work on effects of nuclear explosions in the ionosphere led to the introduction of physics based codes to magnetospheric physics. He is currently PI of the "Fundamental Physics Issues on Radiation Belts and Remediation" Multidisciplinary University Research Initiative (MURI). Dr. Papadopoulos is the recipient of numerous awards, including the E.O. Hulbert Award for Science, the Washington Academy Award for the Physical Science, and the Navy Meritorious Civilian Service Award. He is a corresponding member of the International Academy of Aeronautics and Astronautics, and a fellow of the American Physical Society (APS) and of the Washington Academy of Sciences. In addition to his scientific work he has chaired and served on many NASA, NSF, DOE, DOD, Carnegie Foundation and Eisenhower Institute panels and science boards, including the NASA Space and Earth Science Advisory Committee (SESAC). He received his B.S. in physics from the University of Athens, his M.S. in nuclear engineering from MIT, and his Ph.D. in physics from the University of Maryland. Dr. Papadopoulos previously served on the NRC's Committee on Solar and Space Physics.

Staff

ARTHUR A. CHARO, *Study Director,* has worked since 1995 as a senior program officer with the Space Studies Board. He is the staff officer for the Board's Committee on Earth Science and Applications from Space and Committee on Solar and Space Physics, and he has directed studies that have resulted in some 33 reports, notably the first NRC "decadal survey" in solar and space physics (2002) and Earth science and applications from space (2007). Recently, he served as the study director for the second NRC decadal survey in solar and space physics, a midterm assessment of the Earth science decadal survey, and an assessment of impediments to interagency collaboration on space and Earth science missions. Dr. Charo received his Ph.D. in experimental atomic and molecular physics in 1981 from Duke University and was a post-doctoral fellow in Chemical Physics at Harvard University from 1982-1985 where he worked on developing techniques to enable far-infrared laser spectroscopy of weakly bound complexes formed in a

molecular beam. He then pursued his interests in national security and arms control as a Fellow at Harvard University's Center for Science and International Affairs. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment. In addition to contributing to NRC reports, he is the author of research papers in the field of molecular spectroscopy; reports on arms control and space policy; and the monograph, Continental Air Defense: A Neglected Dimension of Strategic Defense (University Press of America, 1990). Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was a 1988-1989 AAAS Congressional Science Fellow, sponsored by the American Institute of Physics.

DON MONROE, *Consultant,* is a freelance writer covering physics, biology, and technology. Since receiving a master's degree from New York University's Science and Environmental Reporting Program in 2003, he has written for Science, New Scientist, Technology Review, Scientific American, Communications of the Association of Computing Machinery, and the American Physical Society's "Physics" website, among other publications. Prior to that, he was active researcher in condensed-matter physics and semiconductor devices, most recently as a Distinguished Member of Technical Staff, at Bell Labs and related institutions, after getting his Ph.D. in physics from MIT in 1985. In 2002, he served on the committee that investigated alleged fraud in organic materials research at Bell Labs. He is a fellow of the American Physical Society, and a member of the National Association of Science Writers.

E

Selected Publications

The following lists scientific papers related to ionospheric heating that were published in refereed journals during the period from October 2004 through September 2010.

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Bell T.F., U.S. Inan, and T. Chevalier. 2006. Current distribution of a VLF electric dipole antenna in the plasmasphere. *Radio Science* 41:RS2009, doi:10.1029/2005RS003260.

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Bernhardt, P.A., C.A. Selcher, R.H. Lehmberg, S. Rodriguez, J. Thomason, M. McCarrick, and G. Frazer. 2009. Determination of the electron temperature in the modified ionosphere over HAARP using the HF pumped Stimulated Brillouin Scatter (SBS) emission lines. *Annales Geophysicae* 27:4409-4427.

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Bezrodny, V.G., O.V. Charkina, V.G. Galushko, K. Groves, A.S. Kashcheyev, B.J. Watkins, and Y.M. Yampolski. 2007. Observation of ionospheric scintillations of discrete cosmic sources with the use of an imaging riometer. *(Russian) Radio Physics and Radio Astronomy* 12(N3):242-260.

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Burton, L.M., J.A. Cohen, R. Pradipta, A.Labno, M.C. Lee, O. Batischev, D.L. Rokusek, S.P. Kuo, B.J. Watkins, and S. Oyama. 2008. Excitation and diagnoses of cascading Langmuir waves in ionospheric plasmas. *Physica Scripta* 014030, doi:10.1088/0031-8949/2008/T132/014030.

Cohen, J.A., R. Pradipta, L.M. Burton, A. Labno, M.C. Lee, B.J. Watkins, C. Fallen, S.P. Kuo, W.J. Burke, D. Mabius, and B.Z. See. 2010. Generation of ionospheric ducts by HAARP HF heater. *Physica Scripta* 014040, doi:10.1088/0031-8949/2010/T142/014040.

Cohen, M.B., M.A. Go1kowski, and U.S. Inan. 2008. Orientation of the HAARP ELF ionospheric dipole and the auroral electrojet. *Geophysical Research Letters* 35:L02806, doi:10.1029/2007GL032424.

Cohen, M.B., R.K. Said, and U.S. Inan. 2010. Mitigation of 50/60 Hz power-line interference in geophysical data. *Radio Science* 45, doi:10.1029/2010RS004420.

Cohen, M.B., U.S. Inan, and E.W. Paschal. 2010. Sensitive broadband ELF/VLF radio reception with the AWESOME instrument. *IEEE Transactions on Geoscience and Remote Sensing* 48(1):3-17.

Cohen, M.B., U.S. Inan, and M. Go1kowski. 2008. Geometric modulation: A more effective method of steerable ELF/VLF wave generation with continuous HF heating of the lower ionosphere. *Geophysical Research Letters* 35:L12101, doi:10.1029/2008GL034061.

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Hysell, D.L., and E. Nossa. 2010. Excitation threshold and gyroharmonic suppression of artificial E region field-aligned plasma density irregularities. Radio Sci., doi:10.1029/2010RS004360.

Inan, U. S., D. Piddyachiy, W. B. Peter, J. A. Sauvaud, and M. Parrot (2007), DEMETER satellite observations of lightning-induced electron precipitation. *Geophysical Research Letters* 34, L07103, doi:10.1029/2006GL029238.

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Acronyms

AFRL	Air Force Research Laboratory
AIM	atmosphere ionosphere magnetosphere
AIT	artificial ionospheric turbulence
AMISR	Advanced Modular Incoherent Scatter Radar
API	artificial periodic irregularity
APL	artificial plasma layer
BRIOCHE	Basic Research on Ionospheric Characteristics and Effects
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CLUSTER	European space agency mission using four identical spacecraft to probe Earth's magnetosphere in three dimensions
CME	coronal mass ejection
CNES	Centre National d'Etudes Spatiales (space agency of France)
CPCP	cross-polar-cap (or transpolar) potential
DARPA	Defense Advanced Research Projects Agency
dBW	power ratio in decibels (dB) of the measured power referenced to 1 watt
DEMETER	Detection of Electro-Magnetic Emission Transmitted From Earthquake Regions
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
DSX	(Air Force) Demonstration and Science Experiments
EISCAT	European Incoherent Scatter Association
EIW	Earth-ionosphere waveguide
ELF	extremely low frequency
EM	electromagnetic
EMIC	Electromagnetic Ion Cyclotron (waves)
ePOP	enhanced Polar Outflow Probe
EPSCoR	Experimental Program to Stimulate Competitive Research
ERC	Engineering Research Center
ERG	Energization and Radiation in Geospace
ERP	effective radiated power
FAI	field aligned irregularity
FAST	Fast Auroral Snapshot
GHz	gigahertz
GIMA	Geophysical Institute Magnetometer Array
GPS	Global Positioning System

GRACE	Gravity Recovery and Climate Experiment
GW	gigawatt
HAARP	High Frequency Active Auroral Research Program
HF	high frequency (radar)
IAR	ionospheric Alfven resonator
ICD	ionospheric current drive
IM	ionospheric modifications
IRI	ionospheric research instrument
ISR	incoherent scatter radar
ITM	ionosphere thermosphere magnetosphere
LWA	Long Wavelength Array
MEO	medium Earth orbit
MI	magnetosphere-ionosphere
MLT	mesosphere and lower troposphere
MS	magnetosonic
MUIR	Modular UHF Ionosphere Radar
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
O&M	Operations and Maintenance
PFISR	Poker Flat Incoherent Scatter Radar ISR (silent P)
PI	principal investigator
PMC	polar mesospheric cloud
PMSE	polar mesosphere summer echo
RAX	Radio Aurora Explorer
Resonance	Russian-led mission using four similar spacecraft to measure plasma parameters of the Earth's inner magnetosphere.
RF	radio frequency
RIA	radio-induced aurora
RISR	Resolute Bay Incoherent Scatter Radar
ROM	rough order of magnitude
SAID	subauroral ion drift
SAPS	subauroral polarization stream
SAW/SA	shear Alfvén wave
SBIR	Small Business Innovation Research
SEE	stimulated electromagnetic emission
SPEAR	Space Plasma Exploration by Active Radar
SRI	Stanford Research Institute International
STC	Science and Technology Center
SuperDARN	Super Dual Auroral Radar Network
SWMI	solar wind-magnetosphere-ionosphere

TARANIS	Tool for the Analysis of Radiations from Lightnings and Sprites
TEC	total electron content
THEMIS	Time History of Events and Macroscale Interactions during Substorms
UHF	ultrahigh frequency
ULF	ultralow frequency
VHF	very high frequency
VIPIR	Versatile Interferometric Pulsed Ionospheric Radar
VLA	Very Large Array
VLF	very low frequency